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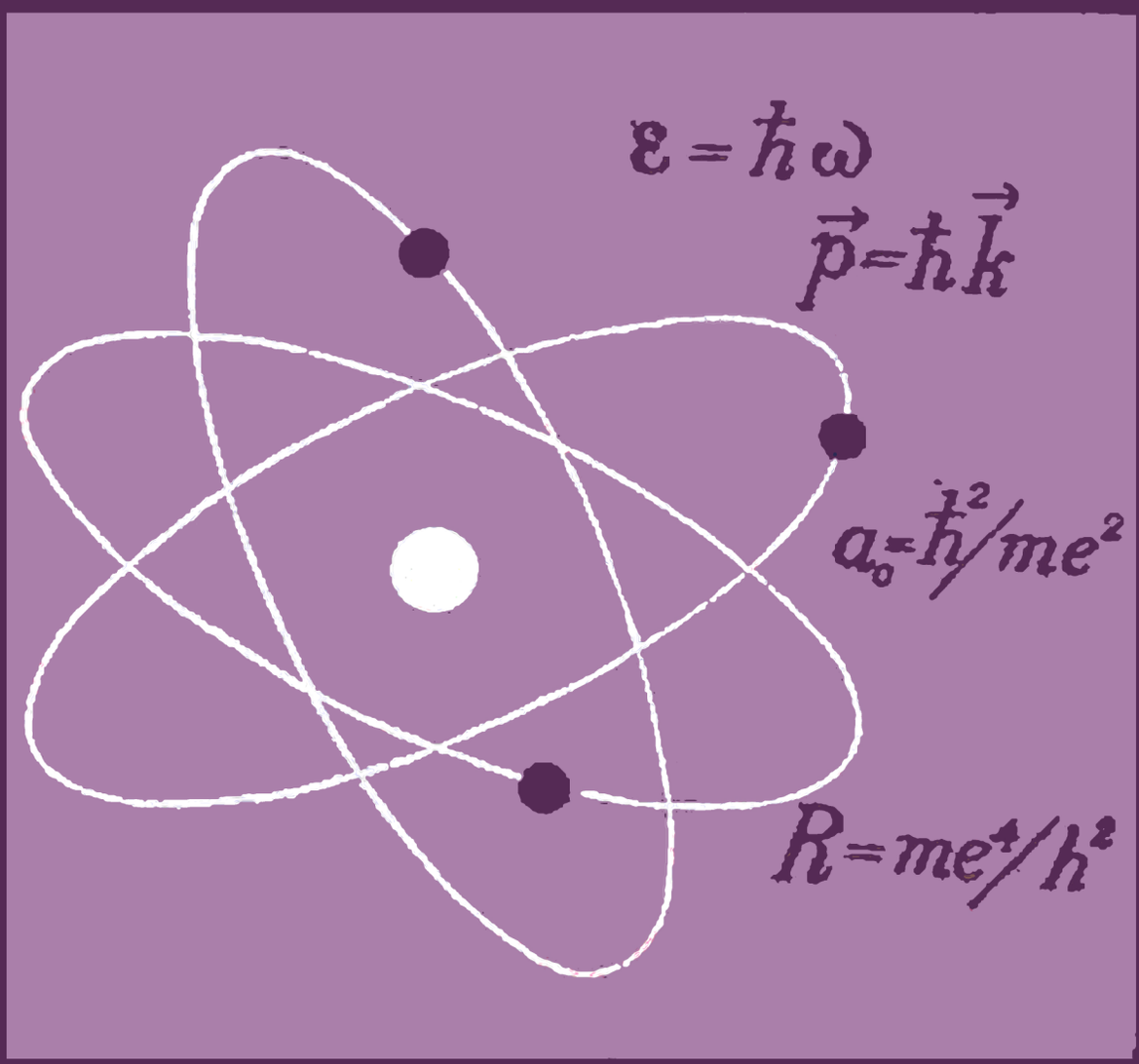

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ИЗДАТЕЛЬСТВО МИР

К. А. Смородинский

ЧАСТИЦЫ, КВАНТЫ, ВОЛНЫ

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Ya. A. Smorodinsky

Particles, Quanta, Waves

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Preface

This book is not a systematic exposition of quantum mechanics. For that it would be too small (and it is difficult to read a book that is both voluminous and popular). But if we may suggest a model (and models will be constantly talked about throughout the book), this book resembles the description of a walk around town. It tells of various things, more or less in the order they happen along the way, without putting them in any order imposed by the historical laws or by the chapters of a textbook; those various things will appear just as houses standing on a street – they may belong to different epochs, which fact does not in the least hamper their being excellent neighbours. Walking along this street was a pleasure to the author who himself witnessed its construction. It is quite possible that the reader could share this feeling. But were it not the case, the walk must be repeated with a better guide – since there can be no doubt that quantum mechanics is very beautiful and that this beauty is discernible by everybody.

Obviously, a knowledge of the high-school course of physics will prove useful in reading this book; knowing, at least in general features, what are diffraction and interference and that energy and momentum are conserved in mechanics will also be helpful. No extensive knowledge is expected of the reader. Just let him be attentive to the world surrounding him!

Introduction

Already 76 years have passed since that portentous evening of December 14, 1900, when Max Planck presented his report in which he publicly formulated for the first time the quantum hypothesis. This day is considered to be the birthday of modern physics.

Despite its considerable age, quantum mechanics still retains its position of a complicated science far removed from the physics taught in school textbooks.

It goes without saying that learning to use the mathematical formulas and equations of quantum mechanics is not an easy task; for example, learning to calculate energy levels of some physical system, for instance, an oxygen molecule or another system of this sort, is rather difficult.

However, the same difficulties are encountered in other sciences as well. Motion of planets, Newton's and Kepler's laws are hardly considered difficult for understanding; but the calculation of the actual planetary orbits and satellite trajectories is extremely complicated and involves the knowledge of mathematics not a shade less thorough than that necessary for molecular calculations. But in spite of this fact we consider the laws governing the motion of planets and satellites to be comprehensible. So mathematical difficulties are not the point here. May be this attitude is rooted in the fact that the phenomena taking place inside the atom are not seen to the eye – but the modern man is accustomed to thinking about and perceiving the phenomena lying beyond the reach of his senses.

And yet the dimensions of the atom play an important part in this strange story. Of course, the smallness of the scale would not be a hindrance if the events inside the atom developed similarly to those in our surroundings. In fact, the laws governing the phenomena inside the atom and in the microcosm in general are quite different from those established by the physicists in the course of studying the macrocosm around them.

But what do these different laws mean? Astronomy will supply us with a clear example.

Motion of Celestial Bodies

People have noticed long ago that some bodies on the earth move along straight lines, e. g. a falling stone or the flame of a fire. The ancients believed that any other motion must have a special reason. However, heavenly bodies followed circular paths as if they were fixed to some unknown rotating spheres. This behaviour of celestial objects did not agree with man's earth-based experience. But the heavenly bodies were so different by their nature from terrestrial objects that it was possible to get used to the idea that the motion of such ideal bodies followed ideal trajectories, and that this motion was governed by a system of ideal spheres. At any rate, this idea became firmly rooted in the human mind and for many centuries was so much devoid of any feeling of astonishment that the attitude toward Kepler's discovery was very seldom serious on the part of his contemporaries.

Nevertheless, both the motion of the planets along elliptical paths and Newton's law of universal gravitation gradually became comprehensible. Nowadays we can only be amazed by the ease with which a schoolboy accepts the ideas of the earth's sphericity and of the planets' motion along ellipses.

Can we expect that the difficulties in comprehending quantum mechanics are only a question of time and that in one or two generations the concept of the wave function will seem to people just as simple as the concepts of coordinates and velocity?

There are some people who still cherish the hope that future will bring such changes to quantum mechanics that everything incomprehensible will disappear and physics will get back its, so to speak, classical appearance. Will it really be the case? That is a difficult question to answer. So far the accumulated experience of progress in science indicates that its history knows no backward motion, and it is conceivable that quantum mechanics will develop still further and will influence our lives even more. Time makes people more and more accustomed to it, and in the development of science a custom is almost always accepted by man as understanding.

And yet quantum mechanics has one very important feature which should be briefly discussed.

Let us return once again to the structure of the universe. The ancients were quite satisfied with the idea that the earth rested on three whales, the whales rested on a turtle, which in turn drifted in the ocean. What happened to the ocean was not clear but even this worried only a handful of people. Nobody was startled by the idea of an infinite ocean. And in our time the idea

of the infinite universe is accepted by many people as absolutely natural; on the opposite, the idea of the space's curvature and of finite models of the universe (regardless of their experimental verification) seems very difficult and even absurd.

Man is apt to accept most easily the idea of similarity. It appears quite natural that the nature exhibits only changes in scale. Dwarfs and giants, footmen and gluttons acted in fairy-tales of old. These characters were pictured exactly as people, only magnified (or reduced) several times in certain parameters. The stories about Gulliver's travels raised no objections, in principle. Quite the reverse, when it became clear that man cannot be simply magnified (in all his linear dimensions) 12 times, this reasoning was accepted as paradoxical.

Galileo was the first to realize that the world holds no place for similarity. In his *Dialogue on Two New Sciences* he discusses at length the foregoing problem: neither a human being nor an animal could survive on our earth if their dimensions were proportionally magnified several times. The reason is extremely simple. If all the dimensions were magnified by a factor of two, the weight of the body would increase eight times; this weight would simply break the bones. To maintain the same strength, the cross section of the bones must increase not fourfold, but eightfold. Therefore, the increase of the size of the animal must be accompanied by its becoming more bulky and thick.

This was a very important discovery. It meant that plants and animals on the earth reach optimal, i. e. most favourable, dimensions. Though the people's stature varies, the spread in height is only about 20 per cent relative to the average value. This is a consequence of the law of universal gravitation discovered much later by Newton. There is no similarity in the field of gravity. Mountains do not reach arbitrary heights, nor oceans arbitrary depths.

Nevertheless, mountains may be higher or lower. But all the electrons *are* identical. There are no 'big' or 'small' electrons. Each electron has the mass 9.10904×10^{-28} g, and nobody has ever observed the slightest difference between two electrons. Of course, this argument makes us think of an analogy for the atom too, viz. that in the long run its dimensions are possibly determined by a hypothetical field, just as the gravitational field determines the dimensions in the 'greater world'.

The answer was far from simple, yet very instructive.

When similarity breaks, new laws are revealed. It is this fact that the human mind accepts with great difficulty. Can the

difficulties inherent to the ideas of quantum mechanics be rel to the violation of similarity? At any rate, this argument is a lo place for us to begin our attempt of exposing quantum mecha

What Happens Within Short Distances

An old idea of Ancient Greeks that everything in nat consists of atoms reappeared in the 19th century. While in 18th century the tiniest constituent particles were referred to monads and no specific properties were ascribed to them, the ato hypothesis became a working hypothesis in the 19th century a was used to provide natural explanation for a large number physical phenomena.

But the hypothesis itself contained a flaw. If one had to ag that the matter which appears as a continuous medium to unsophisticated observer actually consists of atoms, then the ne question immediately arises as to what the atom is constructed

The explanation that the atom has a structure like t solar system seemed quite simple and natural. A tiny heavy nucle is located in the centre, with electrons rotating around it as planet And just as the ancients preferred to be silent as to whe the world ocean ended, it was not questioned at first what wa inside a proton or an electron.

The planetary model of the atom obeyed the similarity princip and easily found room within the framework of customary concept However, this scheme happened to contain a defect which prove fatal to all classical notions. From the point of view of classica physics an electron, rotating around the nucleus, had to emi electromagnetic waves and, losing energy all the time, had inevitabl to fall on the nucleus.

Here we have to mention that our exposition does not follow the historical course of events. The planetary model of the atom was worked out in 1912 in Rutherford's laboratory where Niels Bohr was a visiting scientist. Niels Bohr spent many years elaborating this model, leaving the classical Kepler problem further and further behind in the process. To construct the model he had to introduce new postulates which seemed outrageous to the old physicists.* These postulates were not quite clear to the creator of the theory himself.

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* It is worth mentioning, however, that ideas associated with the Bohr model somehow did not meet such bitter resistance as the theory of relativity. Perhaps quantum mechanics was simply lucky: it did not quickly attract the general attention and its development proceeded comparatively quietly at first.

It was only in 1926 that Heisenberg's quantum mechanics and Schrödinger's wave mechanics, equivalent to the first, were published. This at last gave the new model a firm foundation.

In presenting the modern state-of-the-arts in science we shall keep to the logical sequence of events, which very often does not coincide with historical sequence.

Myriad of Twins

Identical atoms (hydrogen atoms, for example) possess an outstanding property. All of them are indeed identical. (To be precise, atoms are said to be identical if electrons in them are at the same energy levels.) In normal conditions helium consists of two types of atoms: para- and orthohelium, having different momenta. This difference is revealed only in very subtle experiments and we can consider both sorts of atoms to have almost identical properties.

The momenta of two electrons in an atom of parahelium are mutually compensated so that on the whole the atom's momentum is zero.

If parahelium is studied, it comes out that there are no methods which could distinguish between its two atoms. Let us add one atom to a given number of parahelium atoms. It will be lost among other atoms, without any chance to identify the novice. It is also difficult to find one definite particle in a pile of sand, but in principle one can always detect some, even extremely tiny, detail which distinguishes one particle of sand from another. More than that, we can say that there are no two absolutely identical particles of sand. Even two drops of water – a frequently used image of absolutely identical objects – are never exactly equal, at least as far as their size is concerned.

The helium atoms are a different story. They are really indistinguishable. This property of particles in the microcosm is very important; we shall see that many regularly encountered phenomena are determined by just this property.

However, the fact that atoms are indistinguishable should not be identified with the likeness of everyday objects. Each atom of parahelium has zero momentum. The same energy – approximately 24.5 eV – has to be expended to break an electron away from any one of these atoms. The masses of all atoms are identical. But this ends the list of precise characteristics. If we find some way to measure the radius of atoms, for example by illuminating them with short-wavelength light, the results will be different for different runs, although always close to the figure 0.25×10^{-8} cm.

But what then is the difference between an atom and a drop of liquid? Water drops are also of standard size only on the average. It is exactly this property of drops that doctors use while prescribing a certain number of drops of some medicine.

But nevertheless the difference exists. The diameter of a drop can be varied by changing the diameter of a pipette. Drops from a pipette are much larger than those ejected from a sprayer. On the opposite, hydrogen atoms have on the average the radius 0.25×10^{-8} cm regardless of the method by which they were produced. The size of drops is determined by external conditions. The size of atoms is independent of external conditions. *

Why Electons in the Atom Do Not Emit

Let us go back to the electron. The radius of its orbit in the hydrogen atom – this is what determines the dimensions of the hydrogen atom – is about 10^{-8} cm. The velocity of the electron on this orbit reaches 10^8 cm/s. The centripetal acceleration of such motion is so high that by virtue of the laws of electrodynamics the electron must emit very intensively and the atom itself must disappear practically immediately. Nothing like this is encountered in the problem of planetary motion. Since the gravitational interaction is substantially weaker than the electromagnetic one, acceleration of planets is negligibly small. Therefore the emission of gravitational waves by planets is so low that we can safely neglect it for the whole period of their existence. Therefore the classics of celestial mechanics, though they knew nothing about gravitational waves, committed no mistakes when calculating planetary orbits.

The situation in the atom is quite different and, despite all attempts to reconcile the requirements of mechanics and electrodynamics, proved to be a hopeless task. ** It may not be superfluous to remind here that the theory of relativity was also developed when it became clear that mechanics and electrodynamics are irreconcilable.

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* If the temperature of gas is sufficiently high, however, some atoms will become excited and their radii will be increased a little; but these will be 'modified' atoms, not identical with atoms in the ground state.

** It can be estimated that according to the laws of electrodynamics the electron loses (in the hydrogen atom) approximately $(1/137)^4$ of its total energy per revolution. We shall come across the quantity $\alpha = 1/137$ later on.

Atoms possess one more property which cannot be understood if we stick to classical mechanics. The investigation of spectra has demonstrated that the electron orbit-to-nucleus distance cannot be arbitrary. Thus, the radii of orbits in the hydrogen atom (more precisely, the average distance from the nucleus or, which is equivalent, the lengths of greater half-axes of the ellipses) are related to one another as squares of integers. The size of the innermost orbit, i. e. that closest to the nucleus, is 0.5×10^{-8} cm $= a_1$. The dimensions of further orbits increase according to the formula $a_n = n^2 a_1$; $n = 1, 2, 3, \ldots$. This has no analogy in the system of planets, but formulas appear from time to time to calculate the distances – one of them (the Bode formula) is already about 100 years old – but all of them are complicated and not very accurate. In any case nobody doubts that planets can orbit the sun at an arbitrary distance (this even finds its experimental proof in satellites), and any possible relationships can be due only to the evolution of the planetary system.

All other atoms possess a similar property. The admissible orbits form what is referred to as the energy spectrum, since each orbit can be characterized by the energy of the electron. The energy of the electron in an atom can take on one of the values belonging to the spectrum. For instance, the energy of the lowermost level in the hydrogen atom is 13.6 eV (i. e. $13.6 \times 1.6 \times 10^{-12} = 2.18 \times 10^{-11}$ erg). This means that to ionize the hydrogen atom in its normal state we have to apply to it the potential difference of 13.6 V. The energy of the next level is equal to $13.6 : 2^2 = 3.4$ eV.* No electrons can be found between these levels.

Thus, the atom raised two problems: why do electrons not emit when on admissible orbits, and why are there a set of admissible orbits?

Dimension Considerations

Classical physics was not able to answer either of these questions. Moreover, we can be sure that it will never be capable of answering such questions. This statement can be made on the basis of dimension considerations.

To understand how such bold statements can be made, we shall assume that somebody managed to derive, by means of an intricate (but classical) theory, a formula for the radius a_1 of the ground state of the hydrogen atom. We can expect this formula to contain

* The energy of the electron is inversely proportional to its average distance from the nucleus.

some numerical coefficient (which may include, in particular, the number π) and, besides, it must be a composition of quantities characterizing the hydrogen atom. The charge of the electron and proton e and their masses m and M can serve as such quantities. It is not hard to ascertain that no quantity with the dimension of length can be composed out of these three values. If we add to these values the velocity of the electron v, then the length can be made up as e^2/mv^2 and the formula for the radius could be, for example, of the form

$$a_1 = A \frac{e^2}{mv^2}$$

where A is a numerical coefficient. But this formula establishes only the relationship between the electron velocity and its average distance from the nucleus.* However, this formula puts no limits on the values of a_1 and v separately. Therefore we cannot be satisfied with the above formula. No other formula can be derived if we remain within the framework of classical mechanics. If however we deviate from it, we can borrow some other quantities, for instance from the relativity theory, which were already well-known at the moment of discovery of the atomic model. The fundamental constant essential in the theory of relativity is the velocity of light c. Replacing v in the formula by c, we finally arrive at the right type of expression:

$$a_1 = A \frac{e^2}{mc^2}$$

Unfortunately, we cannot be satisfied with this formula either. Let us use it to estimate the energy of the electron in the hydrogen atom. By an order of magnitude it is equal to e^2/a_1, i. e. about mc^2, or 0.5 million eV (MeV). It is too high for the hydrogen level.

Besides, this formula is unsatisfactory from the general point of view. The problem we attempt to solve is not relativistic. Velocities of the electron are small as compared to the velocity of light, and it would be strange if the velocity of light determined the dimensions of the hydrogen atom. All in all, we should better not resort to the relativity theory so soon — we shall need it later.

But then we have to recall the discovery of the quantum of action by Planck. Planck's famous formula

$$E = \hbar\omega$$

* As follows from this formula, $mv^2 = A(e^2/a_1)$, i. e. the kinetic energy is proportional to the potential energy. This is a correct formula, and we can obtain from classical mechanics that $A = -1$.

relates the frequency of emission to quantum energy.* Planck's constant $\hbar = 1.057 \times 10^{-27}$ erg·s establishes a new scale in nature – the energy scale. It was for the first time that a new fundamental constant was discovered on purely theoretical grounds, and one that established something which had not existed in classical physics – an inherent scale of phenomena. Since that moment physicists ceased to satisfy the similarity principle – phenomena with different scales are governed by different laws.

It is interesting to note that other fundamental constants – speed of light, the charge-to-mass ratio for the electron – had already been known by the time Planck's constant was discovered (the second of them – not accurately), but nobody realized yet their relation to natural scales.

Planck's constant enables us immediately to construct the formula for the atomic radius (omitting the constant A):

$$a_1 = \frac{\hbar^2}{me^2}$$

or

$$a_1 = \frac{e^2}{mc^2}\left(\frac{\hbar c}{e^2}\right)^2$$

We have introduced into the second expression the speed of light c (although not long ago we declared that it would be meaningless). But in reality c, of course, does not appear in this formula (c cancels out). This form of writing it becomes helpful if we notice that

$$\frac{\hbar c}{e^2} = \frac{1}{\alpha} = 137.03$$

is exactly the constant we have already mentioned (α is a standard symbol for the inverse of its value). We observe that a_1 is approximately $137^2 = 2 \times 10^4$ times greater than the 'relativistic' radius which was rejected above. It is useful to remember that $e^2/mc^2 = 2.8 \times 10^{-13}$ cm. Therefore a_1 comes out equal to 0.5×10^{-8} cm, which meets our expectations.

Thus it turns out that Planck's constant determines not only the scale of energy but the scale of length as well, by determining the dimensions of the atom. Of course, what was presented above is by no means a derivation of the formula. It would yet be required to prove that the estimate also follows from some theory. This was accomplished by quantum mechanics.

An important thing to emphasize now is that introducing a new

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* Earlier this formula was normally written as $E = h\nu$, where ν is the cyclic frequency. But since present-day physics uses the circular frequency $\omega = 2\pi\nu$, the value $\hbar = h/2\pi$ was introduced to conserve the form of Planck's formula.

fundamental constant imposes restrictions on the similarity of the world. Physical phenomena stop being similar to those of the macrocosm when the dimensions of participants of these phenomena drop down to atomic size. Planck's constant never makes itself felt in our ordinary macroscopic practice – it is just too small to our senses. It is precisely this reason why quantum mechanics seems so difficult.

The theory of relativity also looked difficult since it is hard to realize that the propagation of light is not instantaneous. But once we get used to it, the rest can be explained with no exceptional effort. Whence the conclusion: we should get used to Planck's constant!

Incomprehensible Close by

The reader should not think that quantum mechanics is only necessary to explain the structure of the atom. We are surrounded by numerous phenomena which require the ideas of quantum mechanics for their interpretation. Now it even seems strange how it could be overlooked that classical mechanics is not able to explain the simplest things. At the beginning of the last century solids were assumed to be continuous and the problem of their structure aroused no curiosity, just as the boundless world ocean had not seemed queer to the ancients. But once the atomic theory was born, the very existence of solids became a troublesome fact. Even quite outstanding physicists saw irreconcilable contradictions in the very fact of existence of molecules and took a long time to accept that they do exist.

The phenomena incomprehensible from the standpoint of classical physics are encountered almost everywhere. Electrons moving along a conductor, chemical reactions taking place everywhere, the sun supplying the earth with energy, and, as a matter of course, the functioning of numerous devices in a radio or TV set – all of them requiring the number $\hbar$ for the explanation. It can be said that all formulas of physics can be divided into two types: $\hbar$ is absent from some of them (these are classical formulas); others contain $\hbar$ (these are quantum formulas). The presence of $\hbar$ indicates that the phenomenon in question cannot be described by classical theories, while the absence of $\hbar$ points out that quantum effects are small and that classical physics alone can cope with the describing of the phenomenon.*

* For the sake of simplicity we include the theory of relativity into the framework of classical physics. Effects of this theory are marked in the formulas by the letter c (the speed of light).

Waves and Particles

We have already mentioned that liquids and solids were considered by the scientists of the early last century as continuous media. After the appearance of the atomic theory a new science – statistical physics (or, as it was then termed, the kinetic theory of matter) – was called for in order to make it possible, at least in principle, to relate the motion of the continuous medium to atomic motions. It was at that time that a suspicion aroused that in the long run all natural phenomena can be described in terms of motion of material particles – atoms. However, light definitely did not fit into this picture. The story connected with light is indeed striking: Newton believed light to be a flux of particles. This hypothesis explained the propagation of light through optical devices and in general was satisfactory* until diffraction and interference were discovered. These phenomena indicated that light is formed not of particles but of waves, and at the beginning of the 19th century Fresnel constructed the theory of light in terms of oscillations in some hypothetical elastic medium, i. e. ether. Fresnel's theory described all phenomena related to the propagation of light through lenses and prisms just as well as Newton's. This in itself was strange and surprising: the same physical phenomenon was described by two theories which seemed absolutely incompatible. From that time the wave-particle alternative was to face the physicists for quite a long time.

And indeed during a very long period it was thought that the wave and particle concepts are not even incompatible but mutually exclusive. They were often presented as the 'either-or' logical antithesis. Nobody could imagine that in the twentieth century both theories would merge as if by magic.

If we take a closer look at the properties of waves and particles, we can detect in each of them certain embryos of the other's properties.

In each point (of a homogeneous medium) the light wave propagates along a straight line. The beam of a searchlight looks very much like a jet from a fire-hose nozzle (before it curves down and breaks into drops). Elementary textbooks show how the refraction of light can be described both in terms of waves and in terms of particles. All that is necessary is the assumption that in the medium waves propagate at the velocity n times less than the velocity of light in vacuum (n is the index of refraction),

* Newton's theory could not explain colours, but this fact was simply neglected. The interpretation of colours in terms of mechanics appeared so tempting that discrepancies in the theory were overlooked too readily.

while corpuscles move at the velocity n times more than the velocity of light in vacuum.

On the other hand, waves also propagate in gases which consist of particles, but wave formation requires participation of a large number of particles. Nevertheless waves in a gas cannot be identified with the gas itself. When a wave moves along the surface, it is formed in different places by different particles – the wave transmits velocity and pressure while the particles of water practically do not leave their respective places. A wave propagating along a string does not entrain any metal: each element of the string vibrates but without moving along the string. Therefore a special medium had to be devised for light – the light-carrying ether in which light propagates. But 100 years proved not to be enough for anybody to comprehend the inner structure and composition of this ether.

Finally this idea (at least in its original form) had to be discarded. Now everybody understands (or simply got used to the thought) that light waves are self-sufficient and do not require (in contrast to sea waves) any medium for themselves to exist. In the theory of electricity – electrodynamics – the electromagnetic field appears independently of and is not related to any medium.

This is a very important fact which constitutes one of the basic pillars of the modern theory. And although even Maxwell thought of ether, in fact he needed it only owing to a habit; ether never entered into formulas and even its properties were chosen in such a way that the results were not affected.*

When Michelson failed to detect the motion of the earth through ether, the properties of ether began to look so queer that Einstein decided to kick ether out of physics for good (actually his decision was based not on Michelson's experiments, but this is not important, and we shall keep to the well-worn legend – history finds it more convenient).

Thus to understand the material exposed below one has to get used to the idea that a wave can propagate by itself, not requiring any special medium for a carrier. This is a very difficult idea, one that must be repeated over and over again. But this is not yet a quantum idea – the letter $\hbar$ has not yet appeared!

Light, nevertheless, is not merely a wave. Look at an electric lamp

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* We cannot help recalling Lewis Carrol:

But I was thinking of a plan
To dye one's whiskers green
And always use so large a fan
That they could not be seen.

on your table. The light streaming from it reveals practically no wave properties. It cannot be made to interfere with the light emitted by a chandelier fixed on the ceiling, it cannot be made to go round an obstacle – it propagates along straight paths as if the lamp really emitted minute shot-like corpuscles.

On the other hand, the light generated by a nowadays well-known laser reveals all the wave properties. Light beams from two lasers can be made to interfere. Old textbooks stated that an interference pattern could be produced only by two such beams of light which originated from a very small point source whose light was separated into two parts. At that time it was difficult to talk of interference – the point source, which actually was not needed in the theory, butted into everything. Fortunately, today everybody is aware of the existence of lasers!

It looks as if the light from an ordinary lamp is similar to a flux of particles, while that from lasers to waves. However, we are quite positive (any doubts are groundless) that the nature of light is the same in both cases. Then what is the difference between these two sources of light? To answer this question we must adopt to some extent one more idea – the idea of coherence. (This is also not a quantum idea – without the letter $\hbar$!)

Coherence

Light is known to us as oscillations of the electromagnetic field. Let us remind the reader that the wavelength corresponding, for example, to the red light is approximately 3.4×10^3 Å. The frequency of this light, i. e. the number of oscillations per second, is about 0.8×10^{15} s^{-1}. The product of these two values is equal to the speed of light which, according to the latest data, is*

$$(299\,792\,456.2 \pm 1.1) \text{ m/s}$$

According to such concepts light must propagate in space in such a manner that the maxima of field values are repeated in the direction of light propagation across the intervals equal to the wavelength; and the whole pattern moves in space at the velocity c. In the direction normal to that of light propagation, the phase of

* This value was obtained through accurate measurements of the laser's wavelength and frequency. The accuracy of such measurements is really high. The cited value is obtained as the product of two figures: 33 922.231 376 Å × 88.376 181 627 THz (10^{12} Hz). The new value published in the fall of 1974 is even more exact: 299 792 459.0 ± 0.8 m/s.

oscillations* is the same at each moment on a certain surface — plane if light propagates as a broad beam and spherical if it radiates from a point source.

Wave fronts may be of various shapes, but oscillations of the electromagnetic field at distinct points of space must be correlated to one another so that motion in all the points were submitted to a single rhythm – a single conductor. To be more exact, the phase difference between two distinct points of space remains constant in this field – only then do we see (or record) the progress of the wave. Of course, we could make the problem more accurate by introducing slow variation of this phase difference (observe sea waves' behaviour), but we shall be satisfied with this somewhat simplified picture.

An analogous situation must be observed in the light source. When an excited atom in a hot filament of a lamp emits light, this light is emitted with a definite phase. Another atom emits light with a different phase. From one atom to another these phases vary in a random fashion; besides, various reasons cause random variation of phases with time.

As a result, although each atom creates the light wave, a disordered ensemble of atoms does not produce an ordered field since oscillation phases in this field vary randomly and practically no order can be detected. Such a field can be compared to a violently turbulent rather than to a wave motion.

It is said that such light is not coherent; it cannot interfere since interference requires for the interfering beams to have rigorous distribution of phase difference: otherwise no pattern of dark and bright bands will be produced on the screen.

We can specify a little more here. The light emitted by a lamp does not interfere in the sense that if two mirrors are put at an angle across its path, then lamp images will be seen at the same time in both mirrors and neither of them will hamper the formation of the other: light waves returning to the eye from both mirrors will not mix – instead of amplitudes of electromagnetic oscillations the phase-averaged effects on retina will add up. At the same time the phenomenon of diffraction – deviation from the rectilinear propagation of light (appearance of light behind

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* The values characterizing an oscillatory process (for instance, the electric field) vary periodically like trigonometric functions. The argument of such a function is called the phase of oscillation. In fact we do not give here an explanation to the concept of the phase of oscillation – this is something the reader must know from the textbook, and we assume that he does.

the screen edge) – can be observed since this phenomenon does not involve mixing of two (or more) beams. Non-coherent light can be compared to the sounds from the orchestra. Although all of the instruments perform their parts in perfect accord, a listener in the audience can distinguish the sounds produced by each instrument: these sounds do not mix, or interfere, with one another. Looking at the lamp we can separately see all sections of the filament – light emitted from them does not mix either.

Lasers produce light with a very high degree of coherence (the reason for this will be explained later). The end face of a laser emits light quite unlike the end of a red-hot rod which emits in all directions. A laser emits a narrow beam which traverses hundreds of metres without broadening. This means that a wave field, i. e. oscillations of the electromagnetic field, fill up a cylindrical volume while outside this volume they precisely cancel one another out, producing a sharply bounded surface of the beam. In addition to this the light from the laser is also very intensive, but just now this fact is not relevant. As follows from the general laws of optics, the beam divergence angle is determined by the ratio of the light wavelength to the dimensions of the region of coherence, i. e. the dimensions of the end face area which emits light in an ordered (phasewise), coherent fashion. In high-quality lasers this characteristic is reduced to a few thousandths.

Thus the wave properties of the electromagnetic field are determined not only by Maxwell's equations but also by the properties of light sources. Light from ordinary old bulbs reveals practically no wave properties – a coherent source is required to detect light waves. Considering light in this manner, one cannot help noticing that non-coherent light has very much in common with particles; however, to bring this analogy to the surface we must at last introduce Planck's constant.

Planck's Constant Enters the Theory

Of course, the fact that light propagates along straight lines makes one think of the analogy with the trajectory of a mass point. However, trajectory is not the main characteristic of motion. Mere kinematics is not enough to establish the analogy. A mass point possesses energy and momentum. What are energy and momentum of light emitted by the lamp? It is well known that light exerts pressure on the illuminated surface – this was proved experimentally by Russian physicist P. N. Lebedev a long time ago.

It is common knowledge that light carries energy, in particular the light from the sun. However, right now we are interested in the energy of that portion of light which we want to treat as a material particle. What we mean is, of course, a quantum. We already know that the energy of the quantum is equal to $\hbar\omega$. But does a quantum possess momentum? This question is immediately answered by the theory of relativity. Energy and momentum form a single entity (called a four-dimensional vector); any object which possesses energy must have momentum as well. A quantum too possesses momentum. Its determination is facilitated by introducing a new concept, viz. that of the wave vector. The wavelength λ does not sufficiently characterize the light wave.* One must also fix the direction in which it propagates. A wave is normally described by the wave vector $\vec{k}$ with the direction coinciding with that of wave propagation and the value equal to $2\pi/\lambda$. The coefficient 2π is introduced here in order that the relation

$$c = \lambda\nu$$

be rewritten without coefficients, i. e. as

$$\omega = ck$$

The momentum of a quantum is related to its wave vector by the expression

$$\vec{p} = \hbar\vec{k}$$

These formulas, together with the formula for energy $E = \hbar\omega$, bridge the gap between the world of waves, described by means of ω and k, and the world of mechanics in which momentum and energy reign.

However, one should not hope that at last we can make everything simple and clear just by means of two outstanding formulas. No, the way into quantum mechanics still remains arduous: we have made only the first step by introducing Planck's constant.

How to Trap a Quantum

We encounter the first surprise when we try to understand how a quantum of light can be recorded, emitted, for example, from a laser. It is readily realized that the number of quanta emitted by a laser can be counted: all we need is the quotient of the

* When we mention here the light wave we usually mean a plane wave with a permanently fixed direction of propagation.

energy of radiation to $\hbar\omega$. We have stated that a quantum is the wave with the minimal energy $\hbar\omega$. It can be recorded, for example, in a photographic plate where it is absorbed by a silver atom. But obviously the atom of silver will absorb the quantum in the very place where the atom is localized, and since the absorption of a quantum fraction is impossible, this process will destroy the whole wave pattern occupying a greater space than the silver atom (ideally the whole space).

A quantum of light is absorbed (and emitted) as a particle, and propagates as a wave. Being absorbed, the quantum transfers its momentum to the atom, and in principle the recoil of this atom could be measured. The recoil of this type was first observed in the process of scattering of quanta by electrons (this is the so-called Compton effect). Energies and momenta of a quantum and an electron sum up (in the sense of conservation laws) in the same manner as in the case of a collision between two ordinary particles moving at a high velocity. Quanta should not be compared either to billiard balls rolling along the table or even to projectiles ejected from a gun. Since the velocity of the quantum is c, we must invoke the formulas of the relativity theory. Indeed, it follows from the formulas for energy and momentum of the quantum that these two quantities are related by the formula $\varepsilon = cp$, quite unlike the corresponding formula for kinetic energy in ordinary mechanics. The relativity theory derives another formula for energy:

$$E = \sqrt{p^2c^2 + m_0^2c^4}$$

In this expression m_0 is the rest mass of the particle. If we set $m_0 = 0$, we obtain the relationship for quanta. It is in this sense that quantum is said to possess no mass. Of course, if mass is determined from the formula $E = mc^2$ (this will be, so to say, the motion mass), then we get for it simple but generally useless formula: $m = \frac{\hbar\omega}{c^2} = \frac{\hbar k}{c}$.

Thus we have established that although one quantum forms a wave field, the latter cannot be recorded, a quantum being absorbed as a particle. We cannot measure the field in question at two distinct points and determine, say, the phase difference at these points. Thus the field picture can only be imagined. It is needed to describe the propagation of the quantum since this quantum can be detected in any other point of space.

Alas, once we record the presence of a quantum in one point of space, we completely lose the possibility to record it at

the same moment of time anywhere else; a particle cannot be in two places simultaneously. But a wave can! One sea wave can overturn several boats simultaneously.

In order to be able to measure the electromagnetic field in several points at the same moment and to make sure experimentally that waves do exist, one must first of all have a great number of quanta. It can be said that to measure the phase in a field with an error less than a certain fixed value $\Delta\varphi$, the field must contain at least $N \sim 1/\Delta\varphi$ quanta. Besides, we know that these quanta should be not arbitrary but coherent. However large is the number of quanta emitted by a desk lamp, they do not produce the electromagnetic field and remain merely an ensemble of non-coherent portions of light.

As we know, a source of coherent light is the laser. The nineteenth-century physicists had no laser, so they were powerless as far as the problem of combining waves and particles was concerned. However, it is frightening to think what would happen if Newton were presented with a laser (sent, for example, by some extraterrestrial civilization). It seems doubtful that he would still be able to accomplish anything in science! *

And since nowadays we get used to a laser, this helps us in getting accustomed to Planck's constant.

One old joke is relevant to recall here. This joke compares wire telegraph to a very big dog: when pulled by the tail in London, it barks in Paris. Once this analogy is digested, we can drop the dog and be left with a model of wireless telegraph.

This joke is far from silly. Man grew accustomed very quickly to the idea that conversations can be carried over the wires, and was very much surprised to find out that the same thing can be achieved without wires.

Models in quantum mechanics have the same fate. The model with the dog helps to get used to a new phenomenon; but it should always be kept in mind that our next step will be to get rid of the dog.

Electron. Pauli's Principle

A very unusual rule, viz. exclusion principle, discovered by Pauli, holds for electrons. This principle has no analogies either in the

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* If supercivilized extraterrestrial visitors had ever come to us in the past, they would certainly leave a trace in the form of some instrument incomprehensible to us, and would not resort (in the style of April fools' day practical jokes) to building stone platforms or drawing gigantic symbols.

mechanics of particles or in wave optics. And though the statement of this principle is simple, in fact it reveals profound principles that lie at the very basis of natural phenomena. Pauli's principle states that no two electrons can exist which move in an exactly identical way. For example, the existence of two electrons with absolutely identical velocities is forbidden.* In the case of quanta we considered an exactly opposite situation: the electromagnetic field produced by a large number of absolutely identical quanta.

Pauli's principle was put forth to explain the stability of the atom: to explain why electrons in the atom do not fall down to the innermost orbit; according to this principle, this innermost orbit can house only one electron while the rest of the electrons must fill higher and higher energy levels of the atom.

The derivation of Pauli's principle is based on very subtle relationships between the requirements of the relativity theory and those of the quantum theory of wave fields, and, since classical physics has no analogue to this principle, a clear and illustrative explanation becomes hardly possible. It can be expected that Pauli's principle will considerably impede understanding of wave properties of electrons; and this is indeed the case. Electrons cannot be described in the way we used in the case of quanta because we cannot think of a wave field composed of a great number of absolutely identical electrons. Nonetheless, an analogy with light quanta exists.

De Broglie Waves

Even before quantum mechanics was born, Einstein had realized that atoms of the monoatomic gas must, similarly to photons, reveal wave properties. These properties were predicted to appear as deviations of specific heat values from those calculated from the formulas of classical thermodynamics and, possibly, even as yet unknown interference phenomena. In fact the experiments with interference of particles were carried out not with atoms but with electrons. It was found that if electrons from a point source** are passed through two slits separated by a short distance, then a photographic plate behind these slits will record alternating bands of higher and lower intensity. The experiment appears

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* To be more precise, we mean electrons which have identical spin projections.

** A hot filament. The same Pauli's principle forbids the realization of a laser for electrons, and physicists in this field work in the same manner as the nineteenth-century opticians.

to indicate that the two slits are two coherent sources of waves. Such waves could be produced only by each individual electron, since the source of electrons – a hot filament – emits electrons non-coherently, just as was the case for quanta.

Without quite understanding the details we still can say that an electron is similar to a quantum in the sense that it propagates as a wave and is recorded as a particle; only in this case we cannot explain how to visualize the propagation of electron waves.

Nevertheless we can understand (now, when quantum mechanics has developed into an orderly science) why in 1924 de Broglie suggested a hypothesis that the motion of the electron is tied to some wave motion whose wavelength and frequency are determined by the same formulas

$$\omega = \frac{E}{\hbar}, \quad \lambda = \frac{2\pi\hbar}{p}$$

which have been already written for quanta. For a slowly moving electron (i. e. for an electron with the velocity $v \ll c$)

$$\lambda = \frac{2\pi\hbar}{mv}$$

This value is called the de Broglie wavelength. The meaning of de Broglie's hypothesis was not understood for a long period of time. The author himself refers to a pilot wave that carries the electron on its crest; a good deal of time has elapsed until the idea that de Broglie's wave is the electron itself began to seem acceptable.

The energy of electrons is usually expressed in electron volts. This unit of energy is equal to $1\ \text{eV} = 1.6 \times 10^{-12}$ erg $= 1.6 \times 10^{-19}$ joule.* The formula for the de Broglie wavelength can be written in the form

$$\lambda \cong \frac{10^{-7}}{\sqrt{E}}\ \text{cm}$$

if the energy of an electron is expressed in electron volts. We see that at the energy of 1 eV the wavelength of the electron is many

* 1 electron volt is usually explained as the energy gained by the electron after passing the potential difference of 1 V. This is correct, but we can forget this definition and simply consider one electron volt as an additional unit of energy. (Energy is especially unlucky in that a new unit for it is introduced in each domain of natural science.)

times shorter than that of visible light (several thousand angstrom units; 1 angstrom unit = 10^{-8} cm).

The wavelength of an electron producing X-rays (1-10 keV of energy) is still less by a factor of a few tens. This is why electrons can produce high-quality images of very small objects in electron microscopes. By the way, paths of electrons in the microscope are determined by the laws of mechanics. The wave properties of electrons spoil the image: they determine the resolution of the microscope. We remind here that the ideal optical microscope is also designed according to the laws of the geometrical optics. The electron microscope is often mentioned in literature as an illustration of the similarity between waves and electrons; in fact, the situation is quite the reverse. It is the optical microscope that uses the analogy between light and particle flows.

Capture of slow neutrons by uranium in nuclear reactors is a clear demonstration of the optical properties of particles. The dimensions of the uranium atom (its radius) are about 7 fermis (1 fermi = 10^{-13} cm), so that to an impinging neutron it appears as a platelet with the area of $50\pi \approx 150$ sq fermis. In reality neutrons are captured in such a way that these platelets seem to be several times larger, and the larger the slower the neutron. Theoretically the cross section of the neutron's capture (this is how this area is called) can reach $\pi\lambda^2$, i. e. at the energy of 1 eV it may be as high as 10^{-14} cm^2. Actually only a rare neutron colliding with a nucleus will be captured – in most cases it will bounce away as from an elastic ball. Nevertheless, capture cross sections exceeding geometric dimensions by a factor of tens of thousands are observed experimentally (for example, capture by gadolinium nuclei). It is difficult to interpret such immense capture cross sections if we tend to consider neutrons as particles; but the situation becomes understandable once we treat neutrons as waves.

Diffraction of Electrons

Assuming the reader to have agreed to the idea that in principle an electron can possess wave properties, we return to history and retell him when and how these properties were demonstrated. It must be emphasized once again that understanding of the corpuscular properties of light is reached much easier than that of the wave properties of electrons. In addition, the experimental demonstration of wave properties of electrons is also a more difficult task.

An attempt to establish the similarities between light and electrons must be made among such phenomena in which the wavelength of a quantum and that of an electron are approximately equal. This is extremely difficult in the visible light range since generation of electrons with the wavelength of 4000 Å is practically impossible.*

The most convenient range for modelling is found in the range of the X-ray radiation. X-rays used for the crystallographic analysis of crystals have wavelengths of the order of interatomic spacings, i. e. of the order of 10^{-8} cm. Electrons with energies of about 1000 eV have just the same wavelengths. Therefore we must expect that electrons with energies of several thousand electron volts will exhibit diffraction phenomena in their transmission through crystals. This was really observed by Davisson and Germer in 1927, even before quantum mechanics was discovered.**

When X-rays, i. e. light waves with wavelengths of several angstrom units, impinge on a crystal, they produce vibrations of atoms forming the crystalline lattice. In transferring momentum to atoms, the quanta change the direction of their own momentum, i. e. are scattered. As a result the whole pattern looks as if lattice atoms were converted into luminous points. However, these 'street lights' have one important characteristic. Since all of them are excited by the same wave,*** all atoms oscillate in an ordered fashion, and light waves emitted by them interfere, thus producing an X-ray pattern which makes it possible to decipher the symmetry of atomic sites in the lattice.

If scattering of light in a crystalline lattice were described in terms of corpuscular concepts, then corpuscles scattered by different centres would move independently and produce a continuously illuminated background similar to that created by street lights in a town square.**** Thus the diffraction of X-rays in crystals indicates that light quanta can excite simultaneously many atoms

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* This would require acceleration of electrons by the potential difference of a few microvolts, while even the thermal motion of electrons corresponds to the energy of about 1/40 V!

** But after Einstein had predicted the possibility of observing such phenomena.

*** If a quantum were absorbed by one atom, it would excite only this one atom – while being scattered this quantum excites the whole system.

**** Street lights produce shadows (a corpuscular pattern). Moscow physicists observed similar shadows produced by an atom in a crystal irradiated by a proton beam (Tulinov's shadow method). So here too wave and corpuscular phenomena coexist with one another.

in a coherent way, which can by no means be accomplished by a flux of classical corpuscles.

When a crystal is irradiated by a beam of electrons, these electrons are also scattered by lattice atoms, and in such a way as if atoms became coherent sources of electrons. Therefore, wave properties of electrons result in their coherent scattering on lattice atoms.

The theory of scattering demonstrates that as a result electrons transmitted through the crystal are reflected from crystalline planes so that their direction of propagation makes with the initial direction of incidence an angle satisfying the condition

$$\sin\theta = \frac{\lambda}{2a}n, \quad n = 1, 2, \ldots$$

where a is the interplanar spacing in the crystal (the formula is given for the case of cubic crystals). This formula shows why it is important for the electron wavelength to be small.

If the ratio λ/a were high, we could not record either maxima or minima and could not obtain any information on the structure of the crystal. If λ/a is somewhat less than unity (say, 1/10 or 1/8), several rings are seen, the value of a being calculated from distances between the rings. If, finally, the ratio λ/a is very small, these rings will be spaced very close together and in fact only a shadow will be projected onto the screen. This reflects the general rule of optics which states that if we use the light with the wavelength λ, we cannot resolve images of objects whose dimensions by the order of magnitude are smaller than λ.*

Phonons

It may seem strange that the formula for the diffraction of electrons (quantum effect) did not include the letter $\hbar$. But $\hbar$ was also absent from the formulas for light diffraction. Planck's constant will appear immediately when we start combining wave and corpuscular pictures, i. e. at the point where we leave the solid ground of classical physics.

When electrons are scattered and their direction of motion is altered, they automatically transfer part of their momentum to the lattice. The law diffraction can be rephrased in terms of

* When dealing with a single crystal, the pattern on the screen is not a system of rings but a system of dark spots spaced along concentric circles. Continuous circles are obtained for polycrystalline samples. Details can be found in any treatise on X-ray structural analysis or in a textbook of optics.

mechanics by formulating it in terms of the law of momentum conservation.

If we consider, for the sake of simplicity, a primitive cubic lattice (there are no such crystals in nature) in which the distance between the nearest neighbouring atoms is a, this lattice can receive momentum which is an integral multiple of $2\pi\hbar/a$ and is directed along one of the straight lines joining any two lattice atoms.* If we construct three unit-length vectors $\vec{e}_1$, $\vec{e}_2$, and $\vec{e}_3$ directed along the three edges of the cubic lattice, then the momentum which can be transferred to the lattice is determined by the formula

$$\vec{p} = \frac{\hbar (n_1 \vec{e}_1 + n_2 \vec{e}_2 + n_3 \vec{e}_3)}{a}$$

where n_1, n_2, and n_3 are arbitrary integers (positive or negative). Thus we see that the moment $\hbar$ appeared, definite discrete values of the physical parameter were produced; quantization took place.

The process of electron scattering proceeds as if its collision with the lattice made the electron emit a quantum with the momentum $\vec{p}$. Only this is not a quantum of the electromagnetic field but a quantum of lattice vibrations. This quantum behaves very similarly both to a wave and to a particle, and both these characteristics (a scientist-journalist would say – both its incarnations) are related by Planck's constant. A long time ago Ya. I. Frenkel called these quanta, propagating through crystals, phonons.** Phonons are in many respects similar to particles: they possess momentum; their energy is expressed almost as in the case of light:

$$\varepsilon = vk$$

where v is the velocity of sound. The situation with its rest mass is somewhat more complicated. If we try to calculate the mass by the relativistic formula

$$m^2 = \frac{1}{c^4}(E^2 - c^2 p^2)$$

we obtain that m^2 is negative (since $v < c$). Of course, it would be foolish to apply this formula to phonons, but nevertheless it demonstrates that a phonon is not quite a genuine particle.

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* The allowed values of momentum for crystals with more complicated structures form so-called reciprocal lattices.

** This term opened the way to the whole family of ...ons: rotons in helium, magnons in magnetic materials, polarons in semiconductors, and, finally, mesons, hyperons, etc.

This is absolutely correct: no mass is transferred when a phonon propagates in a crystal; and one cannot imagine a phonon propagating in vacuum – it is essentially a wave in a crystal, and is captured inside it for lifetime. In contrast to photons, i. e. the light quanta for which medium (ether) proved unnecessary, the very nature of phonons requires medium. In this sense the crystal lattice can be called the phonon-carrying ether. The example with phonons is instructive because it shows how quanta are generated in wave motion. This happens when we begin to look into momentum and energy of the wave.

Mössbauer Effect

Quantum properties of oscillations in the crystal lattice are clearly illustrated by the effect of the resonance absorption of quanta by nuclei. As any other quantum system, the nucleus has an energy spectrum; this means that the system, the nucleus, can be found only in a definite energy state. When the state of a nucleus is changed, the nucleus either absorbs or emits a high-energy quantum. Assume, for example, that a nucleus has two states A and B and that state B is characterized by a higher energy than state A. If the nucleus is in state B, it can change to state A by emitting a quantum with the energy determined by the difference between the nucleus' energies in states A and B

$$\hbar\omega = E_B - E_A$$

Conversely, the nucleus may change from state A to state B by absorbing a quantum of the same frequency. Let us take for definiteness a specific nucleus. Let it be the nucleus of the iron isotope ^{59}Fe. This nucleus possesses an energy level of about 100 keV with a comparatively long lifetime. By emitting a gamma-quantum the nucleus switches to its ground state. Now, if our setup is designed in such a manner that this gamma-quantum collides with another nucleus of ^{59}Fe already in its ground state, this second nucleus may be expected to absorb the quantum and switch to the so-called isomeric state.* This process would result in transferring the excitation of one atom to another.

But if we attempted to realize such a process in reality, we would run into complications.

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* This state 'lives' for a comparatively long period of time because of the high angular momentum (spin), which is not imparted easily to a gamma-quantum.

Emission of a quantum is accompanied by a recoil of the atom – it receives momentum with the value equal to (and directed oppositely to) the quantum momentum. The law governing this process is that of conservation of momentum similar to the recoil in a gun from which a bullet is ejected. As a result, a fraction of energy released in the process of discharge of the nucleus is converted into the kinetic energy of the remaining nucleus, while the quantum receives the energy somewhat less than that calculated above.

This reduction of energy will be fatal for our experiment. The second nucleus will be unable to absorb the quantum because it is slightly 'spoilt' and its energy does not match the energy level of the nucleus. Therefore this experiment cannot be carried out with free nuclei. But if the emitting nucleus is in the crystalline lattice and if the sample temperature is very low, then the quanta are unexpectedly 'improved' (this was discovered by Mössbauer) and absorbed by the second nucleus. Everything looks as if the nucleus in the crystalline lattice ceased to be recoiled, as if it ignored the laws of mechanics.

The paradox is immediately cleared when we remember that the nucleus is in the lattice and, having received the recoil momentum, must generate the lattice vibration. In quantum terms it means that the nucleus has to emit a phonon. But since the recoil is very minute, the phonon momentum must also b extremely low. But quantum mechanics points out that the emissio of a low-energy phonon, and at low temperature at that, is very difficult, i. e. its probability is extremely low. Therefore at low temperatures the situation looks as if the nucleus were safely anchored and could not vibrate, so that the recoil momentum was received not by the absorbing nucleus but by the sample as a whole. However, the sample is so heavy that its velocity of recoil is negligibly small, so that as a result all the energy released by a discharging nucleus is imparted to the quantum. Therefore the quantum remains 'unspoilt' and its absorption by a nucleus is observed experimentally. The Mössbauer effect is extensively used in laboratories since the nucleus bound in the lattice proves to be extremely sensitive to the energy of the quantum; its linking in the lattice creates an illusion of an absolutely stationary nucleus – a state absolutely unachievable in a gas for instance.

Many beautiful effects are related to nuclei in the crystalline lattice; they are described in books dedicated to solid state physics. But we have to turn to another group of phenomena.

Scattering of Particles

The investigation of atomic and molecular spectra, and of electronic and atomic collisions made it possible to test the predictions of quantum theory very thoroughly indeed. Nowadays nobody doubts that this theory correctly describes the phenomena of the microcosm. Nevertheless it is always useful to single out those phenomena in which wave properties of particles find their most clear-cut expression. Scattering of neutrons and protons by nuclei must be regarded as one of such phenomena. When energy of the impinging nucleons is high, their wavelengths become less than the dimensions of the nucleus. The wavelength of a nucleon with the energy E million electron volts is equal to $4.5/\sqrt{E}$. For example, at 100 MeV the corresponding wavelength is 0.5 fermi which is less than the nucleus diameter. For such a nucleon the nucleus is an opaque ball. It is known that the deviation of light paths from rectilinear trajectories can be observed in the case of light scattering by a black ball. In the angle of the order of λ/a diffraction bands can be observed (λ is the wavelength and a is the diameter of the sphere). Similar variations of intensity are observed when nucleons are scattered by nuclei: diffraction of nucleons is a well-known phenomenon.

At the time of its development the theoretical description of the electron scattering led to understanding of the physical meaning of the fundamental mathematical object of quantum mechanics, viz. the wave function.

Schrödinger Equation

If we feel sufficiently at home with the fact that electrons possess wave properties, we are fully prepared to the idea that the description of the electron behaviour must be performed in a manner different from that used in classical mechanics. When the techniques of quantum mechanics were being developed, they took two quite dissimilar forms. Heisenberg, who called his theory quantum mechanics, operated with ordinary physical concepts — coordinates, momenta. However, he changed the rules of treating these quantities by substituting the formulas of ordinary algebra by more complicated ones. These formulas were later found to coincide with those used in matrix calculations. Therefore Heisenberg's theory was also referred to as matrix mechanics.

Simultaneously Schrödinger proposed another theory. This theory, which was termed wave mechanics, operated on a quite

new concept, that of the wave function. The wave function satisfied the equation similar to that of heat propagation but modified in such a way that in vacuum it gave the solution in the form of a plane wave, well known from electrodynamics. At the beginning no specific meaning was attributed to the wave function itself; it played the only role: the equation it satisfied could only be solved at definite values of energy. These values coincided with those obtained earlier by Bohr and which were in good agreement with experimental data. Equations of this type – equations with eigenvalues – had already been known before.

The equation describing vibrations in a string gives a classical example of the above-mentioned type of equations. If a string, fixed at both end points, has the length L, then it can vibrate only when the wavelength is an integral multiple of $L/2$: only then can an integral number of half-waves be spaced over the distance L, and stationary points – nodes – will be located at the points where the string is fixed. Both the basic vibration mode of a string and its overtones were well known and served as a starting point for constructing the Schrödinger equation. Electrodynamics contains similar equations – they describe, for instance, oscillations of electromagnetic fields in a resonator. We find that these equations combine a continuous function, for instance, string displacement at the point x (within the string) and discrete values of allowed frequencies. Mathematics has in advance stored an equation for the microcosm description. The Schrödinger equation is fairly complicated and we shall not analyze it here – it rather calls for textbooks. The significance of this equation can be seen in proper perspective if we say that the Schrödinger equation provides a correct quantum-mechanical description of phenomena in all problems we are able to solve in classical mechanics. It was very soon established that both versions of the theory, quantum mechanics and wave mechanics, are in fact equivalent and all formulas of one theory can be converted into those of another theory. However, it was not very easy to understand how to interpret the wave function, i. e. the solution of the Schrödinger equation.

Wave Function

In electrodynamics a field is described by Maxwell's equations, which determine the values of the electric and magnetic fields at all points of space. These fields can be measured by instruments, so they are not worth mentioning any more. But this type of

description is impossible for electrons. Firstly, we have already mentioned that Pauli's principle forbids creation of a classical electron field. But there also exists another difficulty: electrons are charged while quanta are not. Evidently, the rules of the game are different for electrons.

Quantum mechanics reflects a spectacular feature of scientific progress. In the critical moments of the history of science new concepts are not deduced logically from the already familiar knowledge: a logical jump takes place, a new way of thinking and the capability of digesting new notions, no matter how unbelievable they may seem, are created. The trouble is that the human mind is accustomed to function within the framework of a definite scheme, and switching to another scheme proves to be a very painful operation. Nowadays it is hard to understand why the universal ether was considered to be a simpler notion than the electromagnetic field; but even now it is difficult to assume that the wave function is a more elementary image than the image of a material point moving along a trajectory.

Newton's equation describing the motion of a mass point possesses one important, though seemingly quite natural, feature. If at some moment of time a material particle is found at a definite point of space, then according to this equation it cannot be present at any other point.

Equations of quantum mechanics must combine the properties of equations in electrodynamics describing waves, and of those in mechanics operating with such characteristics of a particle as its coordinate and momentum.

This synthesis can be seen in problems of classical optics. If we are not interested in diffraction, optical problems are solved by constructing paths of light rays in the optical system as it is carried out in high-school textbooks. It is quite justified to interpret the rays, drawn while the problem of the microscope is being solved, as trajectories along which the energy of the electromagnetic field propagates. (If this energy is divided by $\hbar\omega$, we can calculate the number of moving quanta as well.) The energy of the electromagnetic field is equal to $1/2(E^2 + H^2)$, i. e. to half the sum of squares of the two fields.

The description of an electron in quantum mechanics follows a similar line. An electron is described by a function $\psi(x, y, z)$ analogous to the electromagnetic field.* However, in contrast to the electromagnetic field the function $\psi(x, y, z)$ was demonstrated

* More exactly, analogous to potentials of this field.

to be complex (and to show it was not easy). As any other complex function, it is characterized by two real functions – the amplitude, or modulus, $|\psi(x, y, z)|$ and the phase α:

$$\psi(x, y, z) = |\psi(x, y, z)| e^{i\alpha}$$

apparently, the phase α regulates interference while the modulus is in some way connected with the corpuscular character of electrons.

During the first period of quantum mechanics the wave function was obtained as a by-product in calculations of energy levels.

When we solve the problem of vibrations of a string or of a plate, then equations of the theory of elasticity determine frequencies of vibrations, and $u(x)$ and $u(x, y)$ give displacements of various points from the equilibrium position in a string and a plate, respectively.

The Schrödinger equation also determines frequencies of the system (or energy values: $\varepsilon = \hbar\omega$); in the solution of the equation the wave function ψ is an analogue of the displacement u. The difficulty is obviously due to the fact that it is not clear what sort of displacement it describes.

But there had been a day when physicists decided to throw away the medium – ether – and grew accustomed to the thought that light waves require no medium to propagate. While interpreting the wave function we must turn to the same idea. Unfortunately we only know how to measure magnetic and electric fields but are in the dark about directly recording the values of the complex function $\psi(x, y, z)$. This fact is a serious obstacle on the way to understanding of quantum mechanics.

So far we are only interested in energy levels and can completely ignore the problem of the physical meaning of the wave function – in fact, the first years of quantum mechanics were marked by different viewpoints concerning this problem.

However, this question acquired principal importance when physicists tackled the problem of scattering of particles, for example, on the Coulomb field of a nucleus. Here it was necessary to calculate the flux of particles, i. e. the number of particles crossing a unit area per second. The analysis of the problem led to a conclusion that the value

$$|\psi(x, y, z)|^2$$

determines the density of particles at the point (x, y, z).*

* The flux of particles (for example along the z-axis) was determined by the formula $j_z = \frac{\hbar}{2im}\left(\psi^* \frac{\partial\psi}{\partial z} - \psi \frac{\partial\psi^*}{\partial z}\right)$.

At first glance one may think that the problem happened to be formulated not for a single particle but for a beam of particles and what is meant is simply a statistical problem. But we already know that in an ordinary source electrons are emitted non-coherently, and so different electrons do not interfere with one another. Therefore we are forced to come to the conclusion that the wave function describes a single electron. But what is then the meaning of the words: density of particles? And it is here that the decisive step is taken, a step which completely demolishes the chain of arguments of classical mechanics. If $\psi(x, y, z)$ describes a single electron, we have to assume that the value

$$|\psi(x, y, z)|^2$$

determines the probability for an electron to be at the point (x, y, z). This means that if we try to determine somehow the electron's coordinates in a hydrogen atom, different experiments will yield different results, and the theory can only predict the probability of a specific result of measurements being unable to predict accurate results.

A source of misunderstanding often lurks in this point. Obviously, only one measurement can be performed with each given atom, or, at the most, several measurements in successive moments of time. We cannot measure simultaneously different coordinates of the electron, i. e. the values of the function $|\psi|^2$ at distinct points of space. This can be realized only for different atoms (or for one atom but at distinct moments of time – a hardly possible experiment). Nevertheless we assume that the function ψ exists in each atom, and measurements of $|\psi|^2$ for different atoms can be conducted only because all hydrogen atoms are *absolutely identical.* This is an important principle of quantum mechanics. Thus we must take for granted (if we want to use quantum mechanics) that the wave function describes the state of an individual electron in spite of the fact that quantum mechanics can be experimentally tested only on a large number of electrons.

Unfortunately, to explain the situation in a more understandable manner is extremely difficult. Recalling the joke about the dog, we throw the model out of the above explanation and from this moment on shall try to tell the reader how the physical universe can be described by means of quantum mechanics.

Uncertainty Principle

It may appear that the description of an electron by means of the wave function is not as accurate as by means of Newton's equations. Let us recall how the problem of the electron's motion in the Coulomb field (or of a planet in the sun's field) is formulated in classical mechanics. Usually it goes like this: the position and momentum of the electron in question are fixed at a certain moment of time $t = 0$. By solving the equations of mechanics we arrive at accurate values of the electron's coordinates and momentum at any other moment of time (before or after $t = 0$).

This problem cannot be solved in quantum mechanics. It could be said in this sense that quantum mechanics is incomplete, were it not for one point.

Suppose this problem was nevertheless given to us; then we must inquire about the origin of the values of the electron's coordinates and momentum at the time moment $t = 0$. Classical mechanics does not doubt that in principle coordinates and velocity of any particle can be measured at any moment of time to any desired degree of accuracy. However, in the case of electrons this possibility was found to be essentially questionable. Indeed, a very accurate recording of the electron's coordinate in an atom requires illumination of this atom by the light with a very short wavelength for the diffraction phenomena not to smudge the electron image. Besides, the energy (or momentum) of light incident on the electron should not be too great in order not to bounce the electron off its position during the recording, i. e. not to alter its state. But these two requirements, so natural in classical theory, are absolutely incompatible in quantum theory. Planck's formula $\varepsilon = \hbar\omega$ dictates that energy smaller than $\hbar\omega$ cannot be absorbed from the flux of short-wavelength quanta, i. e. quanta with a high frequency ω. Accurately measuring the position of an electron, i. e. choosing very high ω, we inevitably impart to our electron a very large momentum without giving any information on the value of this momentum.

Bohr and Heisenberg have formulated the uncertainty principle which, as applied to our problem, states: the product of errors with which an initial coordinate and momentum of a particle can be fixed cannot be made infinitely small, being always greater than $\hbar/2$*

$$\Delta p\, \Delta x \geqslant \frac{\hbar}{2}$$

* The coefficient in the right-hand side depends on the exact definition of what we understand by Δp and Δx. We shall not discuss this problem here.

At $\hbar = 0$ we obtain the classical result. This relationship is called the uncertainty principle; it reflects in a very concentrated form the most profound roots of quantum mechanics.

This principle frequently was the target for criticism. Indeed, it is very painful to believe that the simplest characteristics of a really existing particle cannot be measured. It may even seem that this principle intolerably violates the principles of physics. Naturally, as in many other cases, one strives to find a way to violate the uncertainty principle by attributing it to the imperfections of real instruments. But in fact the uncertainty principle appeared in physics immediately after Planck's constant had been introduced. Once we admit the existence of energy quanta, we simultaneously admit that the effect of the measuring process on the investigated process cannot be avoided. There is no way to combine the quantum and wave properties of photons and electrons and at the same time avoid the uncertainty principle.

Of course, the problem of the uncertainty principle is one of the most difficult in physics, and cannot be proved in this book. But it is important to emphasize once again that difficulties in understanding quantum mechanics are due to its initial principles; once they are embraced (or once we get used to them), the rest of its content follows a profoundly logical and, in this sense, comprehensible scheme.

But let us return to our original problem of initial conditions. We discover that if we tried to describe the motion of an electron in an atom by means of Newton's equations, we would fail because we would find no way to obtain accurate initial data. Equations of classical mechanics are too detailed to be used for solving problems concerning the microcosm.

Equations of quantum mechanics do not require that initial information be so detailed; they determine the development of the system's properties with just such a degree of precision which is compatible with the uncertainty principle. Therefore the accuracy, or completeness, of equations matches perfectly the degree of accuracy of the initial data as allowed by the uncertainty principle.

At this stage we can point out the exact place in the theory in which the logical jump to quantum mechanics happens. This takes place when the development of events is described by the wave function and not by some classical equation average in some way over initial conditions. Quantum mechanics states that the initial state of a system, consisting of many atoms with definite coordinates and momenta, cannot be defined accurately; moreover owing to its very nature it is necessarily described by

a wave function (each atom!). The wave function (its modulus) determines the probabilities of coordinates and velocities, and the dynamics is described not by variation of these parameters but by that of the wave function.

Nothing essential can be added to this exposition without referring the reader to the equations themselves. Of course, a man can become the true supporter of quantum mechanics only by way of solving equations when he himself learns the degree of accuracy in describing and predicting phenomena. The investigation brings full satisfaction only to those participating in it. An outside observer will always be inclined to think that the rules of the game are not fair. However, nobody could suggest better rules (from the spectator's point of view, not from that of the team).

What Else Is Quantized?

So far we have mentioned quantization only once by saying that the minimum energy of the electromagnetic field is found from Planck's formula $\varepsilon = \hbar\omega$. We can deduce therefrom that a variable electromagnetic field with the frequency ω is allowed to have energies which necessarily are integral multiples of $\hbar\omega$: $E = n\hbar\omega$, where the integer n is the number of quanta. The same can be applied to the momentum $\tilde{p} = 2\pi\hbar/\lambda$. But the first theory by Planck did not prescribe what values are allowed for frequency or whether any values can be realized. Therefore, when time came to solve the problem of the atom, it took Bohr's genius to make the next step and calculate the allowed energy levels in the atom.

The difference between the problem of the hydrogen atom and that of the electromagnetic field is that the field occupies the whole space while the atom's dimensions are restricted. Even dimension considerations show that not enough values are available to compose the frequency ω since we have nothing but Planck's constant and the speed of light at our disposal. But frequency cannot be composed of $\hbar$ and c. Indeed, the frequency of an unbounded field can take on arbitrary values.* Such a field is said to have continuous spectrum.

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* The continuous spectrum of frequencies of the electromagnetic field was the reason for the 'ultraviolet catastrophe'; since according to classical concepts the energy per each frequency had to be about kT, the total energy tended to infinity. Planck's hypothesis eliminated this difficulty.

One more constant is added in the case of the hydrogen atom — the electron mass m. We have already seen that this makes it possible to compose both the radius and energy. The energy of the hydrogen atom, or the energy of an electron in the field of a proton, is given in quantum mechanics by the formula

$$E = -\frac{me^4}{2\hbar^2} \cdot \frac{1}{n^2}$$

where n is an integer: $n = 1, 2, 3, \ldots$. The combination of constants in this formula is called rydberg:

$$R = \frac{me^4}{2\hbar^2} = 13.61 \text{ eV}$$

Now the formula for the energy of an electron in the hydrogen atom can be rewritten in the form:

$$E = -\frac{R}{n^2}$$

The minus sign indicates that energy of a bound electron is less than that of a free electron, i. e. that ionization of the atom requires the energy R/n^2 eV to be spent. The formula shows that an electron has an infinite number of states in which it can be found. The lowest of them corresponds to $n = 1$; all of them have negative energies approaching $E = 0$. At the energies greater than zero the electron is not bound to the atom; its energy can then be arbitrary and quantum mechanics imposes no restrictions on its value.

To clarify the meaning of all these formulas, we shall consider a classical circular orbit (with the radius a). The electron velocity on this orbit is found from the condition that the Coulomb attractive force is equal to the centripetal force

$$\frac{mv^2}{a} = \frac{e^2}{a^2}$$

By using this equality we easily demonstrate that the kinetic energy of the electron is equal to one half of its potential energy

$$\frac{mv^2}{2} = \frac{1}{2} \cdot \frac{e^2}{a}$$

Evidently the total energy in this case is also equal to half of the potential energy so that we obtain

$$\frac{1}{2} \cdot \frac{e^2}{a} = R \cdot \frac{1}{n^2}$$

Whence we easily obtain the distance from the proton at which the electron moves

$$a = n^2 \cdot \frac{e^2}{2R} = n^2 \cdot \frac{\hbar}{mc^2} \text{ *}$$

At $n = 1$ this formula coincides with the one we have obtained from dimension arguments.

It can be shown that the equality of the total energy of the electron to half its kinetic energy in the Coulomb field is also valid for arbitrary shapes of orbits, provided we define the potential energy as the mean potential energy. In this case the last formula takes the following form:

$$\left\langle \frac{1}{a} \right\rangle_{\text{mean}} = \frac{mc^2}{\hbar^2} \cdot \frac{1}{n^2}$$

Now let us calculate the velocity on the orbit in question. Again we equalize the Coulomb attractive force to the centripetal force

$$\frac{mv^2}{a} = \frac{e^2}{a^2}$$

Cancelling out a and substituting for $1/a$ the expression given above, we obtain for the root-mean-square velocity

$$\sqrt{\langle v^2 \rangle_{\text{mean}}} = \frac{1}{n} \cdot \frac{e^2}{\hbar c}$$

Now we substitute e in the same formula by its expression via the length a for circular motion:

$$e^2 = n^2 \cdot \frac{\hbar^2}{ma}$$

and replace mv by the momentum p. We obtain

$$p^2 = n^2 \cdot \frac{\hbar^2}{a^2}$$

whence $pa = \hbar n$; $n = 1, 2, 3, 4, \ldots$.

To understand the meaning of this expression, we must establish what pa is in classical mechanics. This is readily achieved: momentum times radius of a circular orbit is the angular momentum of the electron, L,

$$pa = L$$

Therefore the equality $pa = L$ means that the angular momentum can assume values which are integral multiples of Planck's constant:

$$L = l\hbar, \quad l = 1, 2, 3, \ldots$$

* The correct formula for the mean distance gives the value $3a/2$. The value we have obtained is the mean value of $1/a$.

This is a very important formula which is very frequently encountered in various problems. Instead of n we have introduced into this formula another symbol, l; the reason for this is as follows.

The formula reflects one peculiarity of quantum mechanics. The argument, like that presented above, is not rigorous and, generally speaking, we are not justified in our careless resorting to the analogy to quantum mechanics. We cannot be sure that, by writing a classical formula, we may then transfer it without modification to quantum mechanics. Correct formulas show that

$$n = l + 1$$

and not to l as may have seemed. As a result, the angular momentum $l\hbar$ in the least-energy state, for which $n = 1$, is equal not to unity but to zero. The explanation of this discrepancy is due to the condition that formulas of quantum mechanics must correspond to those of classical mechanics when the quantized value is high (i. e., in our case, when $L \gg \hbar$). In other words, the transition to classical physics must take place only for large quantum numbers (large n). And at large n the difference between n and l is indeed negligible.

Thus we come to the conclusion that the angular momentum of the electron (and of any other particle) is quantized. At the same time we can now understand how physics acquired such a strange dimension $[\hbar] = \text{joule} \cdot \text{s}$: this is the dimension of the angular momentum.

Now we can consider the relationship $pa = n\hbar$ in the new light. We know that the wavelength of the electron is equal to

$$\lambda = \frac{2\pi\hbar}{p}$$

Substituting momentum in the last formula by wavelength, we arrive at an elegant expression

$$2\pi a = n\lambda$$

This formula can be interpreted as follows: it shows that an integral number of waves are spaced along the circle with the radius a; one wave at $n = 1$ and, according to what we have said above, it corresponds to the angular momentum $\hbar l = 0$. At $n = 2$ the circumference of the circle is twice the wavelength, etc.

To make our reasoning still more accurate, we remind here that so far we were discussing circular orbits (rather, their quantum analogues).

If the orbit is elliptical, then n is not equal to $l+1$ but exceeds it by an integer. Therefore at a given n it allows orbits with $l=0$, $l=1$, etc., up to $l=n-1$ to exist. This last value of l corresponds to a circular orbit. The orbit with $l=0$ is the most elongated. In classical mechanics we would ascribe to it a trajectory passing through the proton, but this interpretation is, of course, fallacious since any translation of results obtained at small quantum numbers into the language of classical physics can only be misleading.

For example, take the wave function of the electron in the state $n=1$.

It has the form

$$\psi(r)=\frac{1}{a_0^{3/2}}e^{-r/a_0},\quad a_0=\frac{\hbar^2}{me^2}$$

The only feature of this function that could remind us of a trajectory passing through the proton is its reaching maximum at zero argument (at $r=0$). The function is independent of angle so that the probability distribution which it determines

$$|\psi(r)|^2=\frac{1}{a_0^3}e^{-2r/a_0}$$

gives the description not similar to that of motion along the collapsed ellipse, but rather reminds us of the result of averaging such a motion over all possible directions in space.

Quantization of the Projection of Angular Momentum

In classical mechanics the electron's orbit (or the orbit of a planet in Kepler's problem) can lie in one plane. The position of this plane can be defined by a projection of angular momentum onto a certain selected direction in space (let us call it the z-axis).

In quantum mechanics this projection of the angular momentum, L_z, is quantized. It can assume only the values which are integral multiples of $\hbar$:

$$L_z=m\hbar$$

Of course, the quantum number m cannot exceed l, but can be both negative and positive, so that m can take on $2l+1$ values

$$m=-l,\ -l+1,\ -l+2,\ \ldots,\ 0,\ 1,\ \ldots,\ l-1,\ l$$

The case of $m=0$ corresponds in classical mechanics to the orbit lying in a plane which passes through the z-axis. In this case

the position of the plane is completely undefined and the wave function is independent of the azimuth φ. If m is not zero, the wave function becomes dependent on the azimuth. The dependence is extremely simple: it is given by the factor

$$\psi(\varphi) = e^{im\varphi}$$

What causes quantization is quite comprehensible. If φ is changed by 2π, the function must remain unaltered, i. e. the equality

$$e^{im\varphi} = e^{im(\varphi + 2\pi)}$$

must hold, whence we obtain the condition that m must be an integer.

Thus, in this case the condition of quantization follows from the requirement of single-valuedness of the wave function. It can be seen just as easily that this is the mathematical expression of the foregoing condition that the circumference of the circular orbit is an integral multiple of the wavelength. The quantization condition is also obtained in this fashion. Obviously this sort of argument is alien to particle mechanics and reflects the field (i. e. wave) properties of electrons.

Once More on Angular Momentum

Now we are prepared for a more rigorous derivation of quantization of the angular momentum. Since the angular momentum is a vector, it is convenient to consider the square of its length

$$L^2 = L_x^2 + L_y^2 + L_z^2$$

As is usual in quantum mechanics, mean values are meant here. It is clear that the mean value of L^2 will be equal to three times the mean value of L_z^2 since all the three directions x, y and z are absolutely identical:

$$\langle L^2 \rangle_{\text{mean}} = 3 \langle L_z^2 \rangle_{\text{mean}}$$

To calculate the right-hand side of this equality, we shall use the hypothesis that measuring of the square of the projection L_z^2 will with equal probability give any of the allowed values of m^2. Then to calculate the mean value of L_z we must find the arithmetic mean of the following $2l + 1$ numbers:

$$(-l)^2, (-l + 1)^2, \ldots, 0, \ldots, l^2$$

Obviously, we must take twice the sum

$$1 + 4 + 9 + \ldots + l^2$$

and divide it by $2l + 1$. But the sum of squares of l numbers of the series of natural numbers is equal to

$$\frac{1}{6} l(2l + 1)(l + 1)$$

Therefore the sought mean value is

$$3 \times \frac{1}{2l + 1} \times 2 \times \frac{1}{6} l(l + 1)(2l + 1) = l(l + 1)$$

We have thus obtained an important result

$$\langle L^2 \rangle = l(l + 1)$$

It is often mentioned that this expression seems unnatural and a much more natural result would be to obtain l^2. The reason for this is now quite clear: it stems from a well-known fact that a mean square of a value is not necessarily equal to the square of its mean value.

Now we see that it is not the value of the angular momentum but its square that is quantized. This is what causes the uncertainty in the relationship of quantum numbers n and l we were discussing above: l is the maximum value of the projection of the angular momentum, and $l(l + 1)$ is the value of the momentum squared; a somewhat different value related to momentum is averaged in the formulas for the electron energy (automatically in the formulas of quantum mechanics).

Line Width

We have already encountered above that frequency of a transition can be measured to a very high accuracy: this was mentioned in relation to the Mössbauer effect.

Now we shall try to explain why this frequency is fixed very accurately for some of the transitions and not so accurately for others.

While the spectrum of the hydrogen atom is presented for the first time and the formula for its energy levels is derived, it is presumed that this energy is given with absolute accuracy. In fact this is not the case. Let us look at a classical pendulum. Its frequency is known to be related to the length of the pendulum by the expression $\omega^2 = g/l$. However, the pendulum would display this frequency only if it swung without friction. Since in reality friction is always present, the amplitude of the pendulum's swings continuously diminishes. The reduction of the amplitude of oscilla-

tions is apparently due to the work the pendulum does against friction forces, thereby losing its energy. This reduction usually follows the exponential law so that the amplitude of oscillations depends on time as $Ae^{-\gamma t}$. The quantity γ is called the decrement of attenuation; during the time interval $1/\gamma$ the amplitude of oscillations is reduced by $e = 2.72$ times. This time interval is called the lifetime of oscillations. The theory of oscillations shows that this not quite periodic motion can be described as a coherent mixture of oscillations with close frequencies.

It is not difficult to qualitatively understand the appearance of new frequencies, i. e. of line broadening. The period of oscillations is, by definition, a time interval between two moments at which amplitude has identical values. If the amplitude itself systematically diminishes with time, this interval cannot remain constant. Therefore to compose a damped oscillation we have to superpose the whole band of frequencies.

A frequency band, as can be shown, will have the width of the order of γ, i. e. this band will contain all the frequencies separated from the fundamental frequency by the interval of the order of γ in both directions. The concept of the frequency band is expected to be familiar from electronics. Piano strings, tuning forks, etc., have similar frequency bands. The higher is the quality of the oscillating system, the narrower its frequency band. The ratio of the fundamental frequency to the bandwidth is even called the quality factor of the oscillating system.

In the case of emission by an atom the situation is quite similar. Since the atom loses energy by emission, a corresponding relationship analogous to that for a pendulum can be obtained. If the lifetime of the atom, i. e. the mean time of the decay of its excited state, is τ, then the emitted line will be in fact a band with the width Γ connected with τ by the relationship

$$\tau\Gamma \approx 1$$

This expression does not contain Planck's constant, therefore its derivation requires no quantum mechanics. However, if instead of Γ, which is the uncertainty in frequency, we introduce the uncertainty in energy $\Delta E \approx \hbar\Gamma$, a spectacular relationship is obtained between the uncertainty in the energy of a system and its lifetime:

$$\Delta E \geqslant \frac{\hbar}{\tau}$$

We shall yet return to this quantum-mechanical uncertainty relationship.

In the case of the Mössbauer effect a narrow line is produced because the nucleus' lifetime is very long, this effect being observed for nuclei in metastable (i. e. almost stable) states.

An interesting example of a narrow line can be observed in the spectrum of hydrogen. The total angular momentum of the electron and the proton in the ground state of the hydrogen atom is zero. Their inherent angular momenta – spins – are in this state aligned in opposite directions. The state in which the total spin of the electron and the proton is equal to $\hbar$ has a somewhat higher energy. Such states are called triplet states (three projections of spin can be realized: $m = -1, 0, 1$), and the former ones – singlet states. The energy difference between these two states corresponds to the 21-cm line (the energy $E = \hbar c/\lambda \approx 2 \times 10^{-6}$ eV).

The transition between a triplet and a singlet levels in hydrogen atoms is a very rare event. In vacuum a triplet hydrogen atom lives for more than 30 years. Therefore the 21-cm line can be observed in the interstellar space. But in the laboratory even very rarefied hydrogen has to be contained in some kind of a vessel. In a vessel hydrogen atoms collide with walls. The collision may trigger the transition from the triplet state into the singlet one. Therefore, its lifetime in a vessel is reduced. Estimation of this effect is straightforward. The velocity of hydrogen atoms (thermal velocity) can be assumed to be 1000 m/s, and the dimensions of a vessel – about 1 m. Then collisions with walls will take place at intervals of about 10^{-3} s. It is this value (instead of 30 years) that can be taken as an estimate of lifetime. The wavelength of 21 cm corresponds to the frequency $\nu = 3 \times 10^{10}/21$, i. e. about 10^9 Hz. According to the estimated width of the frequency band, this frequency can be measured to the accuracy of three places. Hence, all in all we could obtain 12 digits, the number which was actually realized.

In conclusion it is useful to mention one more effect which also results in broadening of lines. This is the effect of thermal motion. Since atoms move with respect to the observer, emission frequencies will be shifted owing to the Doppler effect; after averaging over different velocities (or, more exactly, over their projections on the line of sight) a frequency band is created its bandwidth is determined by the ratio of the thermal velocity to the speed of light. As a matter of course, the reduction o the Doppler width requires a temperature drop which decrease velocities of molecules.

Laws of Light Emission

We are on the verge of being able to explain the functioning of the laser. The only thing we lack is the laws of light emission discovered by Einstein.

An analysis of emission and absorption of light by an individual isolated atom is a standard problem of quantum theory. For this case the theory calculates the formulas determining the probability for an atom to jump from one state to another, i. e. the formulas defining the process of absorption of light impinging on the atom. The atom in this situation is assumed to be in vacuum so that the emitted light goes to infinity. But the problem may be re-stated. We can ask what the atom's emission will be if it is not in vacuum but in the electromagnetic field. Nowadays it is not difficult to imagine a vessel filled with electromagnetic field; this is either a resonator well-known in radioelectronics, or a waveguide – a pipe along which the electromagnetic wave propagates. Let us place an atom into such a resonator and observe whether the surrounding field affects its emission. It is not difficult to understand that appreciable effects can be expected only if the frequency of oscillations in the field is equal (or close, within the bandwidth) to the frequency of light which the atom can absorb or emit. This problem had arisen and had been solved even before quantum mechanics appeared, viz. in connection with studying the conditions of equilibrium between atoms and radiation. In the nineteenth century it was already understood that the methods of statistical physics can be applied to the electromagnetic field, and that the concepts of energy, pressure and temperature are applicable to radiation fields. Therefore we are justified to discuss equilibrium conditions and how the temperature of atoms and radiation is equilibrated. It is assumed obvious that the probability of absorption of a quantum of a field (with a fixed frequency) is proportional to the number of quanta contained in the resonator. Apparently, the probability of absorption must be such that in each moment in the equilibrium conditions the number of absorbed quanta should be equal to the number of emitted quanta.*

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* As usual, in considerations of this type we assume that the temperature T is not zero, therefore part of the atoms is in the excited state.
Their number is determined by the Boltzmann formula

$$n \cong e^{-V/kT}$$

where V is the excitation energy of the atom.

The argument can be as follows. Let the field contain N quanta. The probability of absorption of a quantum, according to the above arguments, must be equal to aN, where a is the coefficient calculated from standard quantum mechanics which determines the probability of absorption of one quantum. The probability to emit this quantum back must also be equal to aN. Were it not so, the number of quanta in the field could not remain constant and would either increase (in case the probability of emission is greater than aN) or decrease (in case this probability is less than aN).

Now we know that after one quantum has been absorbed, the number of quanta remaining in the field is $N-1$; at the same time the probability of quantum emission, as we have just established, must be equal to aN.

From this we easily conclude that when there are N quanta in the field, the probability of emission is $a(N+1)$. This is Einstein's law which is stated as follows. The ratio of the emission probability A to the probability of absorption B is equal to

$$(N+1):N$$

It is noteworthy that the derivation of this formula (which is often considered difficult) is elementary and at the first glance does not involve ideas of quantum mechanics (no $\hbar$ appears in the formulas). But in fact the derivation makes use of a very important property of quanta: their indistinguishability, identity. We used this property when we were speaking of emission and absorption as about a change in the number of quanta by unity, and not as about a process happening to a given, selected quantum. We know that this consideration presumes coherence of oscillations in the field and cannot be found in classical mechanics of a system of particles. The calculation of coefficients A and B was the last step on the way to derive the formula for distribution of the equilibrium radiation obtained by Bose, who applied the laws of quantum statistics to radiation regarded as the gas of photons.

Einstein's relationship was proved to be valid not only for photons but also for any particles with integral values of spin, for example for pions.

The relationship becomes quite different for electrons, protons and other particles for which spin is fractional (equal to the odd number of halves). In the process of emission the electron's momentum is changed. If the system contains other electrons with the same momentum, then Pauli's principle does not allow for this

electron to switch into an occupied state (with the same spin projection), so that emission will not be realized. Therefore when considering the emission of light by a system of particles, we must take into account Pauli's principle. Therefore, while in the case of light the presence of quanta enhances emission, for electrons occupied states forbid this emission. If we considered the process of generation of electron-positron pairs by light and their annihilation, we would obtain for the ratio of the emission to absorption probabilities the quantity $(1 - N) : N$ when the state is occupied ($N = 1$), i. e. the generation into this state is forbidden. When the state is vacant ($N = 0$) there is nothing to annihilate.

Spontaneous and Stimulated Emission

A simple reasoning has led us to the conclusion that the probability of quantum emission by an atom is proportional to $N + 1$. A possible interpretation is that radiation is divided into two parts: one is independent of whether there are any quanta in the system at all, and the other is proportional to the number of quanta in the system. The former is called spontaneous emission, and the latter induced, or stimulated, emission. For a long time the existence of stimulated emission was regarded as a purely theoretical effect, until Fabrikant experimentally demonstrated it in 1948.

Functioning of two exceptional devices – maser and laser (Basov, Prokhorov, Townes) – is based on the effect of stimulated emission. These two instruments make it possible to produce high-intensity beams of coherent microwave or light emission.

Laser

Functioning of lasers is based on two principles: the stimulation of light emission under the action of the electromagnetic field, and the reduction of line width by increasing the lifetime of the emitting system. The first laser was a rod made of ruby. In this mineral it is possible to produce conditions for a high number of electrons to occupy excited energy levels. We cannot dwell here on how such population inversion is achieved (high number of electrons in excited states and low in the ground state); suffice it to say that a multitude of such methods exists now for the purpose.

Two mirrors are installed at the ends of the ruby rod so that the emitted light reflected by mirrors remains inside the rod for

a comparatively long time (usually the number of reflections reaches several hundreds). Reflections can be said to prolong the lifetime of the system, which, as we know, makes the frequency band very narrow. But mirrors play another role as well. They help accumulate the radiation and increase the number of quanta with the given frequency and direction (standing waves are created, as in a string). The accumulated radiation induces, accelerates discharges of excited states, and this produces an avalanche-like triggering of practically all excitations so that a powerful narrow beam of light bursts out of the laser's end face (one mirror is semi-transparent and transmits a sufficiently powerful beam). All we should be able to do is to continuously produce excitations that will be triggered immediately once the number of excitations has exceeded a certain threshold level.

The realization of this idea was, of course, arduous, but all the principles involved therein were fairly old. Light from a laser is coherent to a high degree by the very essence of the phenomenon.

Electrons in Solids

Pauli's principle allows us to understand how the electrons behave in solids. If atoms were classical objects, nothing would stop the solid from collapsing, and the fact that solids resist external forces and tend to maintain their volume would look as an unexplainable paradox. If for simplicity we forget about atoms and imagine electrons as the electron gas contained in a bounded volume, this hypothetical model will make it possible to visualize the operation of Pauli's principle. Though the gas model seems to be very far from reality, the description it provides for many properties of solids is far from inadequate so that it will be useful to expose its features.

If we consider the case when the temperature of this gas is low, Pauli's principle can be used as follows. According to the uncertainty principle, for each electron $\Delta p \, \Delta x \sim \hbar$. Let us draw a diagram of electrons' momenta, marking on the axes the three components of the momentum of each electron. Then we can assume that per each two electrons (two because of the spin) a cubic cell with the volume of $\hbar^3$ must be assigned on the momentum diagram. If the number of electrons is high, they will have to occupy all the least-energy states at the absolute zero in order to satisfy Pauli's principle and in order not to exceed the limit of two electrons per each cubic cell. The states with energies less than a certain value E_0 will be shown in our diagram by a sphere

with the radius $p_0 = \sqrt{2mE_0}$ and the centre in the origin of coordinates. The volume of this sphere is $4\pi p_0^3/3$, and the number of cubic cells it contains is

$$\frac{4\pi p_0^3}{3\hbar^3}$$

We assume this value to be the number of possible states. If electrons are tightly packed, the number of states will be equal to $n/2$, where n is the total number of electrons in the selected volume. Since we have chosen the volume 1 cm^3, n is simply the electron density.

Thus we arrive at the formula

$$\frac{4\pi p_0^3}{3\hbar^3} = \frac{1}{2} n$$

We deduce that even at the absolute zero electrons do not stop but possess a substantial energy which is readily estimated. Assuming that each atom supplies the electron gas with one electron (the rest remain bound on atomic orbits), we obtain $n \approx 10^{22}$-10^{23}. Using this value we derive that electrons possess energies up to

$$E_0 = \frac{p_0^2}{2m} = \left(\frac{3}{\pi}\right)^{2/3} \cdot \frac{\hbar^2 n^{2/3}}{8m} \cong 1 \text{ eV}$$

Atoms in the classical ideal gas reach such an energy only at temperatures of the order of 10 000° K. Thus it is not strange that pressure in the electron gas should be high. It reaches 10^5 atm. This figure explains the reason for the existence of solids.

A sphere of the radius p_0, discussed above, is called the Fermi sphere, and the corresponding energy is called the Fermi energy.

Superfluidity

The situation is quite different for photons. Pauli's principle does not forbid them to occupy the lowermost state, and Einstein's coefficients even stimulate them to collect, condense in this state. This phenomenon is called Einstein's condensation. Extremely striking properties of liquid helium are connected with it. Helium differs from all other elements in that at normal pressures it remains liquid down to absolute zero. This violates the general rule according to which all motion is frozen out at absolute zero and atoms align into a symmetrical crystalline

lattice. Of course, this does not indicate the failure of fundamental concepts since this rule is valid only in classical physics. This is not the first example of violation of the rule in quantum phenomena. Pauli's principle forbids electrons in metal to stop. However, the case of helium differs from that of the electron gas in that helium atoms do not obey Pauli's principle. There is a general rule according to which only particles with spins equal to 1/2, 3/2, etc. obey Pauli's principle. But particles with integral spins (photons, helium atoms, pi-mesons) are not subject to Pauli's principle; as we have already said, they even tend to occupy in a coherent manner the least-energy state.* Then, recalling photons which also cannot be turned into a solid, we should not be too much surprised by helium's behaviour. Still, the comparison to photons is not too convincing. It could be expected that helium must behave rather like classical spheres weakly interacting with one another; helium is a noble gas and does not form molecules. But the key to its strange behaviour lies exactly in this weak interaction between atoms.

As a result of the weakness of this interaction, helium remains liquid down to extremely low temperatures since comparatively low velocities of atomic motions are sufficient to withstand the interaction forces. If the events were to develop according to the rules of classical mechanics, helium would finally freeze at sufficiently low temperatures and at any, even very low, pressures. However, quantum-mechanical effects come into play. At such low temperatures helium acquires wave properties. The wavelength of helium atoms can be estimated and compared to their dimensions. We can expect that wave properties will be manifested when both these values – wavelength and dimensions – are of the same order of magnitude. The radius of a helium atom is half that of a hydrogen atom (owing to twice the charge of its nucleus) and is determined by the formula

$$r = \frac{\hbar^2}{2me^2}$$

The wavelength is $\hbar/m_{\mathrm{He}}v$. Here m is the mass of an electron, and m_{He} is the mass of a helium atom. Equalizing these two quantities, we obtain the velocity v and calculate the kinetic energy

* The behaviour of particles with half-integral spins is said to be described by the Fermi-Dirac statistics, while that of particles with integral spins by the Bose-Einstein statistics. At high temperatures the theory transforms into the ordinary classical Boltzmann statistics.

$$\frac{m_{\mathrm{He}}}{2} = \frac{4m}{m_{\mathrm{He}}} \cdot \frac{me^4}{2\hbar^2}$$

The quantity in the right-hand side is the already familiar rydberg, i. e. the bond energy of the electron in the ground state of the hydrogen atom equal to 13.6 eV. The mass ratio is 1/4000, therefore the kinetic energy calculated above is about 0.005 eV. This means that the wavelength of an atom with the energy of 0.005 eV will be reduced to atomic dimensions. The temperature of 1° is known to correspond to the energy of 1/10 000 eV.* Therefore, the range that interests us stretches up to several tens of degrees.

Thus, at very low temperatures helium can acquire new quantum properties remaining liquid. This is really the case. At the temperature of 2.2° K (at atmospheric pressure) helium becomes superfluid – i. e. helium's viscosity drops down to zero, and as a result it can flow without friction through very narrow slits.

Superfluidity was discovered by P. L. Kapitza and explained theoretically by L. D. Landau.** In the state of superfluidity helium is a quantum system in its ground state. Changing the velocity of liquid helium, slowing it down, requires generation of vortices, i. e. of non-homogeneous regions of liquid flow. These vortices can be regarded as elementary excitations, rotons, whose generation is determined by the quantization conditions. It is important that, like other quanta, a roton cannot have an arbitrarily small energy, and thus cannot be born at low temperatures. The generation of excitations, viz. rotons, is a characteristic property of the quantum liquid. It became possible to describe by means of such concepts a considerable number of phenomena observed in helium. By studying these phenomena we reveal quantum-mechanical properties of liquids similar to atomic properties but observed on a macroscopic scale. The roton gives an example of a macroquantum produced by a large number of atoms. A certain analogy can be traced between the flow of liquid helium and the behaviour of the electromagnetic field in the laser.

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* This follows from the equality $eV = kT$, where k is the Boltzmann constant.

** N. N. Bogoliubov and R. Feynman made a very significant contribution to the development of the modern theory of superfluidity.

Superconductivity

Another well-known example of a quantum phenomenon of a macroscopic scale is superconductivity. It was discovered in 1911 by Kamerlingh Onnes and for a long time puzzled the physicists. At first glance this phenomenon is very similar to superfluidity of liquid helium.

We can conjecture that electrons also form a quantum liquid which in its ground state flows through the crystalline lattice without resistance (i. e. without friction). However, this analogy is substantially downgraded by the fact that electrons possess spin. As we know, electrons are subject to Pauli's principle which does not allow for all electrons to occupy the lowermost level and to turn into a coherent quantum superfluid liquid.

And nevertheless the analogy works. The solution of the paradox was simple, but digging it out was a matter of considerable time.

Two electrons with oppositely directed spins, as it happens, are attracted to each other and form a weakly bound system, viz. a Cooper pair (Cooper is one of the trio of the physicists who developed the theory; two others were Bardeen and Schrieffer). It may appear strange that two electrons, two particles with the same negative charge, should be attracted to each other. Indeed, in vacuum they would be repulsed according to Coulomb's law. But moving in the field of lattice ions, which are positively charged, they generate in this lattice phonons that are absorbed by other electrons. Everything proceeds as if electrons were exchanging phonons (similarly to their exchange by photons in vacuum). The result of such an exchange is the mutual attraction of electrons which leads to formation of Cooper pairs. Cooper pairs have zero spin, and behave very similarly to helium atoms in the state of superfluidity. The hypothesis of the Cooper pair proved exceptionally fruitful. Nowadays the basic phenomena in superconductivity became comprehensible. As a matter of course, the understanding of the actual theory of superconductivity is a difficult task: this theory uses a complicated mathematical apparatus.*

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* Soviet physicists made an especially significant contribution to the development of the theory of superconductivity: the names of Landau, Ginzburg, Bogoliubov, Gorkov, and Abricosov ought to be mentioned in the first place.

Superfluidity of Helium^3

Helium has a second, rare isotope with mass number 3. Its spin is one half and in contrast to its heavier partner helium^4 it is a fermion. Therefore it was assumed for a long time that it cannot be superfluid. And that conclusion is true when the temperature amounts to some tenths of a degree (Kelvin scale, of course!). However, at much lower temperatures weak interaction between helium atoms gives birth to some kind of Cooper-like pairs, and the superfluid state can in principle be realized. Experimentally the transition into the superfluid state was discovered at a temperature of 2.6 millikelvins (2.6×10^{-3}° K). It is the first phenomenon in the new field, viz. millikelvin cryogenics, which looks extremely attractive and fruitful.

Quantization of Magnetic Flux

Another interesting phenomenon related to superconductivity is quantization of magnetic flux. This is one of a few cases when Planck's constant can be measured, in principle, in a macroscopic experiment.

The current flowing along the ring made of a superconductor (a superconducting torus) generates the magnetic field. The flux Φ of the magnetic field through the ring opening is determined by the value of the current.

If the current were normal, as in ordinary wire circuits, then the flux Φ and, hence, the current could have arbitrary values. But superconductivity is related to a quantum coherent state which, like an electron in the atom, is described by a wave function. It can be shown on the basis of general properties of wave functions in quantum mechanics that in going around the ring the phase of the wave function increases (as for any other wave). The difference between a circular and a linear wires is that when we move along the former we return to the starting point. Clearly we must require that even the phase of the wave function be unaltered as a result of circling the ring, i. e., to be more exact, the phase must be altered by an integral multiple of 2π: $\sin(\varphi + 2\pi) = \sin\varphi$ and $\cos(\varphi + 2\pi) = \cos\varphi$.

We cannot help noticing that this condition is very similar (and indeed it is) to a condition that an integral number of waves should be spaced on the circumference of the ring. We must take it for granted here that one turn changes the phase of the wave function by

$$\frac{2e}{\hbar c}\Phi$$

Equalizing this value to $2\pi n$ ($n = 0, 1, 2$) we obtain that the flux through the ring can have only the following values:

$$\Phi = \frac{\hbar c}{e} \pi \cdot n$$

It is natural to call the quantity $\pi\hbar c/e$ the quantum of the magnetic flux. If, in addition, we measure the electron charge in the CGSM system of units, then one quantum is equal to $\hbar/e$. Numerically this is equal to $10^{-27}/1.6 \times 10^{-20} = 0.6 \times 10^{-7}$. This value is quite macroscopic and it is quite possible to produce one quantum of flux in a ring 1 mm in diameter. A quantum of flux can be carried from place to place. If we distort the ring, the current in it will change so that the flux Φ will remain constant. The current will neither damp out since the ring is superconductive, nor will the deformation of the ring lead to emission of electromagnetic waves – this annular current is similar to a hydrogen atom, only enlarged in size.

We must, however, remark that a hydrogen atom is not always very small. There are atoms in the outer space which get excited to the 100-150th state ($n = 100$ or 150). At $n = 150$ the radius of the corresponding orbit is $n^2 = 2.25 \times 10^4$ times greater than that in the ground state and is about 10^{-4} cm = 1 micron!

Going back to our superconducting ring we can point out once again that it is difficult to devise a better demonstration of the concept of quantum. This example is literally handed down to us by nature as a museum exhibit, which can be stored in a showcase and transferred from place to place. Numerous entertaining experiments can be held with such rings, but of course only when superconductivity becomes a standard subject in lectures. For example, we can imagine an eight-shaped superconductor (having two holes). If the current in it flows in such a way that its directions around both holes are opposite, the directions of the magnetic field in the holes will not be the same so that the magnetic lines of force will interconnect. We shall thus obtain a magnet with two poles at the sides. The behaviour of such current rings is not analogous to that of classical current contours described in textbooks, and their theory is a beautiful example of the application of quantum theory to phenomena readily observed by a naked eye.

Josephson Effect

The discovery of one very interesting phenomenon related to quantization of superconductors made it possible to measure the $\hbar/e$ ratio by means of a voltmeter.

We won't describe the theory of this phenomenon in great detail, but just present the essential facts.

Imagine two pieces of a superconductor separated by a thin layer of an insulator. Current cannot pass through such a junction. The potential difference V being applied to this junction, superconducting electrons tunnel through the insulator and in the process emit the microwave radiation whose frequency is determined by the expression similar to Bohr's formula:

$$\hbar\omega = 2eV$$

The factor of two in the right-hand side of this equation is caused by coupling of electrons into Cooper pairs which hop as a unit. This emission was indeed observed, but another effect, reciprocal to the one discussed above, proved more convenient for practical purposes. The junction was illuminated by radiation with the frequency ω and the potential difference was varied. When $2eV$ reached the value of $n\hbar\omega$ ($n = 1, 2, ...$), the current in the superconductor changed jumpwise. Thus, knowing ω and V, the experimentor was able to measure $\hbar/e$ very accurately.

The significance of this experiment is apparent: for the first time a fundamental constant characteristic for the microcosm was measured in a macroscopic experiment.

On the other hand, Josephson's experiment allows us to compare a reference volt unit to fundamental constants and thus establish reference electrical units not bound to imperfect instruments. In principle such a reference volt unit can always be prepared in a laboratory and there is no need to compare numerous instruments with a unique artificial reference instrument.

The length and time reference units have been referred to the wavelength and frequency of atomic oscillations for a long time. Now the reference volt unit joins these two.

The Invisible

Since we are not careful about logical links between the pieces of our story, we may tell the reader about one more experiment, which became feasible only after lasers had been developed. Light from the laser is so powerful that, if it be directed into a vessel (a tube) filled with gas, we can create the conditions in which all atoms of the gas absorb light and change to the excited state.*

* In fact only one half of the atoms can be excited. In this situation the number of emitted quanta is equal to that of absorbed ones. Hence, the number of quanta in the laser beam remains constant during its passage through the gas.

Once this situation is reached, the gas is unable to absorb any more light with this frequency and becomes transparent, i. e. invisible. Thus the old idea of invisibility came to be realized, but actually only for the light of one predetermined frequency. This effect is used for high-precision measuring of spectra. This requires a laser with tunable wavelengths. Its light is passed through a tube with the investigated gas. A small fraction of the laser beam is directed by means of an optical system into the same tube but from the opposite end. The moment the intensive absorption of light sets in (and this will happen when the laser's wavelength coincides with the wavelength of the investigated transition in the atom), the probing beam is transmitted with a zero absorption. Thus the researcher will measure the wavelength.

It is very important that this sort of measurement deals only with the atoms which have a zero component of velocity in the direction of the beam. This is easy to understand if we mention that any moving atom will have, owing to the Doppler effect, different values of energy levels as seen from the opposite sides of the tube. At one end of the tube the atom is seen moving from the observer, and at the other end moving towards the observer. Thus the effect of invisibility works only for the atoms at rest.

This observation gave birth to a new kind of high-resolution spectroscopy.

Similarity in Nature

We began our story by saying that there is no similarity in the world. We also said that similarity is found only in classical physics. Moreover, the law of similarity should be regarded as its most typical property.

No experiment in classical physics can measure the absolute scales of phenomena. This is why obsolescent textbooks of physics always described the reference units of metre and kilogram. A unit of time, i. e. the second, was earlier associated with the motion of the earth which is not exactly a fundamental approach.

The appearance of the theory of relativity and quantum mechanics changed the whole picture of nature: the atomic transitions give us the scales for time and length and the mass of elementary particles the scale for mass. The physical world was proved to contain the scales of phenomena, which cannot be changed arbitrarily.

The quantities establishing the scale of the physical world are called the fundamental constants.

The dimensionless ratios of fundamental constants are all of great significance.

At present we do not know what stipulates the values of such dimensionless constants as, for instance, α*, but unexpectedly we discover that not a single constant may be changed by us in the up-to-date picture of the world drawn by physics. It seems that our world is designed in such a manner that all its scales are stipulated by certain yet unknown laws. It is hardly possible that any different world can exist. The laws of nature are striking in their mutual interconnections, and man's experience makes us feel certain that in the long run these links will also be perceived.

We have learnt a bit of the laws reigning in the microcosm. Now we are ready to make a rather long trip into the strange world of elementary particles where even the simplest things look very different. It is really a strange world: nothing of this sort could be dreamed of by physicists of preceding generations. Let us start a new tour.

Elementary Particles: What We Know and What We Try to Understand

All natural phenomena are based on simple phenomena involving atoms and molecules. Even in biology it was found that the fundamental processes are most effectively studied at the cell level. This tendency was even more pronounced in physics. Since the end of the last century physicists have gone deeper and deeper into the range of short distances and time intervals expecting to find those tiniest building blocks of which the universe is constructed, and to study the laws of nature governing their behaviour.

It seemed probable for a long time that as we pass from smaller particles to still smaller ones, the picture simplifies, and thus we should succeed in constructing the world surrounding us out of a very small number of identical parts.

In passing from the molecule to the atom, from the atom to the atomic nucleus, and from the nucleus to nucleons and electrons, the physicists gradually began to feel that the end of their search was within reach. The world was getting simpler and it seemed that a few more steps would be enough to grasp the fundamental

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* There exist beautiful formulas for α. For example, $1/\alpha = 4\pi^3 + \pi^2 + \pi = 137.0363$. However, all of them are devoid of any physical meaning.

laws of nature, which would make it possible to explain and describe all the phenomena in our world. The arrangement of the world seemed especially simple in 1932. However, contrary to all expectations, the simplicity proved to be illusory. New discoveries convinced the scientists that the world is incomparably richer and more complicated.

Rutherford's discovery of nucleus in 1911 was a new frontier from which we may date the study of the nucleus and later of elementary particles. In only two decades physicists managed to cover the road from atoms to nuclei, thus diminishing by ten thousand the scale of the objects of investigation. But then the pace was slowed down drastically.

Although 50 years have passed since Rutherford's discovery, physicists in the best laboratories around the world, equipped with gigantic accelerators, only covered the range from 10^{-13} to 10^{-14} cm, i. e. reduced the scale by mere 100 times as compared with the range in which Rutherford himself worked. Nature erects more and more obstacles confronting further progress of the research.

Nevertheless, very much has been accomplished, and each year brings in new discoveries. Instead of the most fundamental laws the physicists had to face a new world with a tremendous variety of particles and phenomena.

Nowadays physicists know scores of particles which are called elementary. These particles are born and perish in the nuclei; they disintegrate, decay, transform into different species. It is difficult to understand all that happens to elementary particles.

The invisible world of elementary particles looks really mysterious. Our understanding of the interrelations between phenomena is quite poor, our concepts of the microcosm are still far from complete, though more than once did it look as if we were close to the completion of the picture. Yet there was time when everything looked bright – at the beginning of the thirties, after neutron was discovered. The structure of the atom appeared strikingly simple.

The 1932 Nucleus

As we have already mentioned, by 1932 physicists' efforts seemed to have been rewarded. The structure of the atom and of the atomic nucleus looked elegant and simple.

The atom consists of a nucleus with electrons distributed around it. The number of electrons Z is equal to the nucleus' charge

and determines the atomic number of the atom (i. e. of the element in the Mendeleev periodic table *). The nucleus consists of positively charged protons and of N neutral neutrons. The number of protons is Z, so that on the whole the atom is neutral. The total number of particles in the nucleus is $A = Z + N$ (N is the number of neutrons). The number A is called the mass number and is almost equal to the atomic weight.

Actually the atomic weight differs to some extent from A. The reason for this is well known. The protons and neutrons (the common term for both is nucleons) are bound to one another. To dismantle the nucleus into separate nucleons, certain energy must be spent. According to the law $E = mc^2$, any increment of energy increases the mass of the system; therefore the mass of the nucleus M is less than the sum of the masses of N neutrons and Z protons.

We also want to remind here that atomic masses are measured in atomic mass units, or amu. These units are chosen so that the mass of the carbon isotope C^{12} is exactly 12 amu.

The masses of elementary particles are usually measured in energy units, MeV. The masses of proton m_p, neutron m_n, and electron m_e are, respectively,

$$m_p = 938.26 \text{ MeV}; \quad m_n = 939.55 \text{ MeV}; \quad m_e = 0.511 \text{ MeV}$$

The picture of the atom as outlined above appears quite complete. But this is not quite true. What is lacking in this picture? Very little: an explanation of how neutrons and protons are bound together in the nucleus.

Indeed, what are the forces against which the work must be done to break the nucleus apart? The answer may be fairly simple: nucleons are bound by a new type of forces – nuclear forces. At first glance this answer is quite satisfactory. We can even say a few words about these forces. In contrast to electric forces they are of short-range nature. Their action becomes negligible at distances greater than approximately 2×10^{-13} cm; but at smaller distances they are stronger than electric forces. The energy due to electric repulsive forces between two protons at a distance of 2×10^{-13} cm is 0.7 MeV. The energy due to nuclear attractive forces between two nucleons at the same distance from each other is approximately 20 MeV.

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* We remind here that Mendeleev knew nothing about the charges of nuclei and nonetheless, by distributing the elements according to their chemical properties, did not make, from the standpoint of the modern atomic physics, a single mistake.

An attentive reader could remark that at infinitely short distances the energy of electric repulsion becomes as high as desired since it is inversely proportional to the distance between two charges. However, this argument is not correct since a proton is not a mathematical point but is distributed in space, and its field at distances less than 10^{-13} cm cannot be represented by that of a point charge.

At the same time a proton cannot be described simply as a tiny charged ball since different parts of this ball would be repulsed by one another and the proton would burst into pieces. Thus the proton can be neither a mathematical point nor a physical ball.

The problem of the inner structure of elementary particles has cropped up a long time ago. Already at the end of the last century Lorentz posed the question about the shape of the electron. It seemed that quantum mechanics which helped to decipher the structure of the atom could do the same as regards the structure of the electron. But neither quantum mechanics in its initial form, nor the theory of relativistic quantum fields proved capable of finding the key to the problem of stability of elementary particles. They failed to explain why the masses of elementary particles have the experimental values. Some of the scientists expected this problem to be analogous to the problem of energy levels in the hydrogen atom; however, nobody even succeeded to formulate this problem correctly.

Nevertheless, if we disregard the proton's dimensions, the 1932 picture of the nucleus looks fairly acceptable.

Physicists 'only' had to introduce a new type of forces and thus complete the description of the nucleus. Physics, however, does not admit new hypotheses quite so simply. Introduction of new forces creates new problems.

Forces and Fields

Long time ago, for example in Galileo's time, it was believed that two solids can interact only if they come into direct contact, i. e. if they push each other. Action at a distance seemed then absurd. Kepler was the first to attribute to the sun the ability to affect the motion of planets, and the first to relate the motion of the moon to high and low tides on the earth. However, these ideas proved unacceptable even to Galileo.

Action at a distance had the right to exist only in Newton's mechanics. But once physicists accepted the idea that two gravitating bodies act on each other at a distance and that two charged

balls also interact at a distance, they were forced to face a new problem: By what means does one body act on the other? How does one charge 'feel' the other at a distance? There was time when distinct types of substances, or corpuscles, were attributed to forces, so that at the beginning of the nineteenth century a system of seven types of corpuscles, or fluids, was developed: positive and negative electricity, north and south magnetism, light, heat and atoms of matter. In this system different types of forces act in different fluids independently without transforming into one another. Science of the time was not aware that heat may be converted into electricity and that electricity gives birth to magnetic forces.

Therefore each force appeared as an independent phenomenon, and physicists at the beginning of the twentieth century counted the number of forces encountered in nature, just as at the end of the nineteenth century they counted the number of distinct elements, and just as the twentieth-century physicists are busy counting elementary particles. Whatever will they count in the next, twenty-first century?

The natural scientist who had put an end to the idea of the invariability of forces and who discovered their common nature (common not for all of them yet, only for electric and magnetic ones) was Michael Faraday.

In 1821 Faraday repeated Oersted's experiments with the magnetic effect of electric current, carried out a year before, and came to the conclusion that the forces are directed tangent to the circles around the direction of the current flow and, in contrast to electric forces radiating from a charge, have no apparent source. The magnetic forces, described by Faraday as systems of lines of force, were looked upon as independent entities filling the space around the current. This was an important stage separated by a comparatively short step from the concept of the electromagnetic field. This concept was introduced by Maxwell only after Faraday's death. But the full significance of this new concept was realized only after the theory of relativity had been developed.

Since no action can be transmitted at the velocity greater than that of light, any interaction between two bodies must propagate through space at a finite velocity. From this we come to an important conclusion. If, for example, one charge is displaced, the second charge * cannot 'feel' the change in the force immediately

* We assume for the sake of simplicity that charges are fixed to springs so that the force acting on the charge can be found from the extension of the spring.

but will 'feel' it only in a time interval equal to the ratio of the distance between the charges to the speed of light. If we set an arrangement of several charges, the first to 'feel' the change of the field will be the one placed closer to the displaced charge. The action of the electric field propagates through space.

Thus we have particles and fields that transmit interactions between particles. Again the picture is almost complete. But we know that light is emitted only as quanta (Maxwell was not yet aware of this!). Hence, a field cannot be a continuous medium. The field must consist of quanta, and modern physics demands that this principle be valid not only for the electromagnetic field, which is responsible for the electromagnetic interaction.

If forces act between particles, then there is a force field, and if there is a field, quanta of this field must exist, i. e. again new particles, which in turn must interact. The story begins to look like an endless tale. Thus to solve the old problem and find out which is a more fundamental notion – a field or particles generating this field – is not an easy venture. Similarly, the question about the composition of a particle becomes equally entangled. Atoms consist of electrons and nuclei. Nuclei consist of protons and neutrons. And what does the proton consist of?

What Does the Proton Consist of?

First of all let us try to use the most daring answer: the proton does not consist of anything, it is an elementary indivisible particle. Such a statement would be completely acceptable to the last-century atomists, but it cannot satisfy us. And we are dissatisfied not for any lofty reasons but simply because it contradicts the experiment.

If a proton is illuminated by a beam of high-energy photons, the collision between a proton p and a photon γ may give birth to a new particle – a positively charged pion (or π^+-meson), while the proton will be converted into a neutron n. This reaction is written in the form:

$$\gamma + p \rightarrow \pi^+ + n$$

It looks as if the proton consisted of a neutron and a pion. However, the same collision may generate one neutral pion and leave the proton intact:

$$\gamma + p \rightarrow \pi^0 + p$$

This reaction rather indicates that the proton consists of itself and a neutral pion. We say 'consists of itself' (however silly it may sound) because in the long run the proton remains exactly the same as before the reaction, i. e. these particles are identical. Now this reminds us of a fairy-tale about an unchangeable dollar bill, which remained a dollar however much of it was spent. But the reader should not be too much surprised – really, the world we are now entering indeed reminds us of a fairy-tale.

If the energy of the proton is sufficiently high, several pions may be produced in the collision:

$$\gamma + p \rightarrow \pi^+ + \pi^- + p$$

or

$$\gamma + p \rightarrow \pi^+ + \pi^- + \pi^+ + \pi^- + \pi^0 + p, \text{ etc.}$$

(watch out for the net charge to remain constant!). If we add to this reaction the reactions taking place in photon-neutron collisions:

$$n + \gamma \rightarrow \pi^0 + n$$

$$n + \gamma \rightarrow \pi^- + p$$

$$n + \gamma \rightarrow \pi^0 + \pi^0 + n, \text{ etc.}$$

then the question of the proton structure becomes tangled up even further.

If the energy of photons is increased still more, for example to the level obtainable on the Yerevan accelerator (recently nicknamed Arus, which is both a poetic feminine name in Armenia and the abbreviation for the Armenian Accelerator), we shall observe even more surprising reactions as

$$p + \gamma \rightarrow p + p + \bar{p}$$

The proton is converted into two protons and one antiproton ($\bar{p}$). We could say, of course, that a proton incorporates two protons, but the meaning of such a statement is hardly comprehensible.

Gradually we come to the conclusion that the question as to what the proton consists of is simply meaningless. We are not used to such situations in our everyday life, but nonetheless this is the case. Evidently, the question of the colour of a positron is meaningless. Only the scholars in the Middle Ages were sure that all questions were meaningful, and that even the question as to how many angels can stand on the point of a needle can be answered. The question as to how many pions there are inside a proton is equally fallacious, although our knowledge about pions is immeasurably more extensive than that about angels.

A Far-Fetched yet Useful Analogy

Let us leave nucleons for a while and for further acquaintance with particles move into the country.

Sitting on the bank of a swift river, look at the surface of the water. You will notice how small and big vortices, or eddies, are streaming down entrained by the flow. It seems that these vortices live their own life. They move along their paths and can collide with one another almost like particles in mechanics. But their life is not eternal, they emerge and disappear, their number constantly changing. We cannot find out where an eddy vanishes. There is no sense to question whether the newly-born vortex is the same that has disappeared a few minutes ago. The strange thing is that such questions do not even come to us on a river-bank. But once the subject is nucleons, we for some reason are eager to raise those questions, although the pictures in these two cases are more similar than it may appear.

If we could arrange a collision of two photons or, and this is already feasible in modern laboratories, a collision of a high-energy positron and an electron, both particles would disappear leaving in their place mesons, protons and antiprotons. The particles can be most various – the important point is that the energy of colliding particles should be sufficient for generating new ones (according to the formula $E = mc^2$). New particles appear in vacuum just as vortices on the smooth surface of the stream. But vortices are formed by water, and what about the source of particles? It is ether (ether once again!) – a substance which fills the whole space and which reacts to the input of energy by generating particles.

Of course, this is by no means the last century's ether – an infinitely permeable, infinitely elastic medium – but something vaguer. Therefore physicists avoid referring to it as ether and just say 'vacuum'. However, the properties of this ether are very complicated, and have nothing in common with emptiness in the 'there is nothing' sense. What is the 'vacuum' of modern physics? What does it consist of? In this place we should better not answer all of the questions and frankly say: 'We do not know.'

This is nothing to be ashamed of. Science in its development only pushes away the border line of the perceived and clears the investigated region of contradictions and mysticism. But the frontier of the terra incognita, concealing the keys to our today's problems, is always in full view. More and more courageous minds get involved in search of solutions.

Indistinguishable Nucleons

Having reached the border line of the investigated area, let us return to our protons and pions. These two types of particles are sharply distinct. Pions can originate and disappear, three pions can turn into five; a pion may disappear having collided with a proton.

Neutrons behave quite differently. Nobody has ever observed a neutron to vanish completely: at most it can turn into a proton. Inside the nucleus a proton can be converted into a neutron as well. But neither can a proton disappear. Only mesons can do that. Nucleons (protons and neutrons) can only transform into one another. In a nucleus such transformations are so frequent that both particles become indistinguishable: they are almost identical.

But in what manner do they become identical? First of all we have to make a reservation. Two protons, if located at a considerable distance, cannot be mistaken for each other. Nobody can doubt that protons, bombarding a target in Geneva, are accelerated in the Geneva accelerator, not in the Serpukhov machine. But if a proton and a neutron are inside the atomic nucleus, it is impossible to distinguish between them.

In the nucleus a proton and a neutron can exchange a pion (as a ball) and switch charges. The proton will emit a positive pion and will turn into a neutron (I). The neutron, in its turn, will capture the newly-born pion and will thus be converted into a proton (II):

$$\text{I. } p \rightarrow n + \pi^+$$

$$\text{II. } n \text{ (another one)} + \pi^+ \rightarrow p \text{ (a new one)}$$

This process proceeds very rapidly. The emitted pion moves at the speed very close to that of light, and since nucleons in the nucleus are at a distance of about 10^{-13} cm, they exchange pions, which takes about 10^{-23} s. From the standpoint of modern experimental techniques this process can be considered instantaneous. Therefore a nucleon is constantly changing – now it is charged and then neutral. Roughly speaking, a nucleon spends half its life as a proton, and half as a neutron. In this sense these different particles can be considered identical.

Thus considering the meson field – the field of nuclear forces – we come to one more conclusion: inside a nucleus protons and neutrons are identical particles.

The Law of Energy Conservation in the Microcosm

When we were discussing pion production in a collision of a fast proton with another nucleon, the energy required for its production was extracted from the kinetic energy of the proton itself. What then is the source of energy for a pion generation inside a nucleus? Evidently, it is not the kinetic energy of nucleons. If the nucleons' energy were sufficient to generate pions, the latter would radiate from all nuclei until this energy were spent.

To eliminate the contradiction we have to assume that in reality pions are not emitted – they are said to appear virtually. This means that nobody can record the intermediate stage of exchange when one nucleon has already ejected a pion and the other has not yet captured it. At any rate this cannot be done unless we spend so much energy to record a pion that this would be enough to release a pion.

The law of energy conservation in quantum mechanics may be violated, but only if this violation lasts for a very short period of time, τ, less than

$$\tau \approx \frac{\hbar}{\Delta E}$$

where ΔE is the excess or defect of energy. If this inequality is valid, the violation of the energy conservation law cannot be either detected or used for any type of a motor. By describing interactions as ball games (and this is the only description consistent with the requirements of the relativity theory), we have to give up the rigorous application of the energy conservation law. However (and this is what makes quantum mechanics powerful), these violations of the fundamental law leave all its consequences unaltered and have not changed in the least the physicists' attitude towards the impossibility to design a perpetuum mobile. The violation of the energy conservation law is rooted in the fact that the very concept of energy changes its meaning in the microcosm. So the restriction of the applicability of the conservation law is the price paid for the attempt to retain the concept of energy as unaltered as possible.

The above inequality allows the mass of a pion, i. e. of a quantum of the field of nuclear forces, to be estimated. If the pion mass is denoted by μ, the corresponding energy will be μc^2. Therefore, the emission of a pion violates the energy conservation law by μc^2. But this violation cannot last longer than $\hbar/\mu c^2$. The distance covered by a pion during this time is not greater than

$$\lambda \approx \frac{\hbar}{\mu c^2} \cdot c = \frac{\hbar}{\mu c}$$

Therefore, if a quantum of the field has a mass μ, then only those charges can interact which are spaced apart by not more than λ. For the electron mass this quantity is called the Compton wavelength (it enters into the formula of the Compton effect for light scattering by electrons) and is equal to

$$\lambda_C = 3.96 \times 10^{-11} \text{ cm}$$

Since the action radius of nuclear forces is approximately 1.3×10^{-13} cm, i. e. about 300 times less than λ_C, the mass of a pion must exceed that of an electron by a factor of 300. (In fact the pion mass is equal to 273 electron masses.) We remark in passing that the mass of a quantum of the electromagnetic field is zero, and therefore the action radius of the electromagnetic forces is infinitely large.

One more note. Remember that electric lines of force fan out from the charge centre like needles from a hedgehog. Wherever a sphere is drawn with its centre at the point in which the charge is placed, the number of lines crossing the sphere remains constant since the lines never interrupt.

The situation is different if we try to construct the lines of nuclear forces. Since these forces decrease faster than Coulomb forces, the number of lines of force crossing the sphere will decrease as the distance from the nucleon increases; these lines will disappear into the empty space.

On Coulomb's Law and Nuclear Forces

Our notes on electric lines of force touch on a very interesting property of fields. Since Coulomb's work it is known that two electric charges are attracted or repulsed (depending on signs of the charges) by the force inversely proportional to the square of the distance between them. Whence follows an important theorem (called the Gauss-Ostrogradsky theorem). This theorem can be stated in the following way. If the direction of force is shown by a line of force (lines of force of the magnetic field are given in most of textbooks for high schools), and if the density of lines is the higher the greater the value of the force (the greater the electric field), then we obtain a convenient map of the electric field.

Such maps have been used for long time. If now we surround the charge by some closed surface, it is readily seen that, regardless of the shape of this surface (provided the charge in question is inside the surface), the number of lines of force cutting this

surface remains the same. If for simplicity we draw not an arbitrary surface but a sphere with its centre at the point where the charge is placed, then the theorem states that the product of the electric field E on this surface by the sphere's surface area is a constant quantity equal to the charge value (in SI units). Indeed, the electric field decreases like $1/R^2$, and the area of the sphere is proportional to R^2, where R is the distance from the charge. Therefore this product remains constant.

The theorem actually contains a somewhat broader statement: this property remains valid for any closed surface, not only for a sphere. If the surface is not spherical, we must divide it into small unit-area regions, measure the component of the field normal to each region, and sum up all these quantities over all the regions of the closed surface. This operation is the integration over the surface. Whence follows an important conclusion. However large the distance from the charges, in principle we can always measure their values by recording the map of the field. According to the theorem, contributions from all the charges outside of the closed surface will cancel out after integrating the field over the sphere's surface, and the result will give the value of the charge inside the surface.

This property of the electric field reveals its long-range character, or the fact that the photon mass is zero. By the way, by measuring the earth's magnetic field and using the consequences of the Gauss-Ostrogradsky theorem it was found possible to determine the upper boundary of the photon mass, i. e. of the value of the mass which the experimentors could detect (but did not!) in these experiments. The experimental results indicate that the mass of a photon is at least less than 10^{-47} gram, i. e. less than 10^{-20} of the electron mass. In other words, the experiment detects no deviations from Coulomb's law up to a distance of about 30 000 km from the earth!

In the domain of nuclear forces the situation is completely different. Owing to their short range of action the nuclear forces are not subject to the law of conservation of lines of force, therefore the number of nucleons cannot be determined by the net field of nuclear forces at a large distance as we could do for charged particles on the basis of their electric field. One consequence, important for our world, follows immediately. A large mass of matter must be neutral: all charges of protons must be cancelled out to a high degree of accuracy by the proper number of electrons. But the sources of nuclear forces, viz. nucleons, need not be compensated for by a corresponding number of antinucleons

since the lines of nuclear forces disappear even without such compensation. Thus in the long run the very existence of our world proves to be related to the short-range character of nuclear forces.

For a long time it seemed that this precluded any reliable measurements of nuclear forces, that the price for their short-range action was practical impossibility to detect them at a considerable distance. However, subtle experiments on scattering of protons by protons made it possible to prove conclusively that nuclear forces at large distances are described by Yukawa's* potential, which depends on the distance as

$$Y(R) \propto \frac{e^{-R/\lambda}}{R}$$

where λ is that very Compton wavelength of the pion which has been discussed above. Yukawa's potential differs from Coulomb's potential

$$Q(R) \propto \frac{1}{R}$$

by the factor in the numerator rapidly diminishing with the distance. The number e is approximately equal to 2.72, and the above factor decreases 2.72 times when R increases by λ.

Thus Yukawa's law is not less real than Coulomb's law though its verification took incomparably more effort. Unfortunately, as physics progresses, the experiments become more and more complicated, and now we can only think with awe about the times when almost any phenomenon could be studied at a low cost. However, the new discoveries led to a large-scale understanding of the forces of nature: the work of scientists and material expenditures are repaid a hundredfold.

But let us return to the nucleus of 1948 – when the feeling of order and well-being in the understanding of nature reached its climax.

The 1948 Nucleus

At the end of the forties the nucleus was pictured not as a rigid system of 'packed together' protons and neutrons, but as a system of rapidly moving nucleons, which intensively exchange pions – both charged and neutral.** This exchange keeps the

* After the Japanese physicist who predicted the existence of pions.

** Nucleons and mesons are the members of the family of strongly interacting particles, or *hadrons* (this word was coined by L. Okun). Electrons, muons, and neutrinos are called *leptons*.

nucleons close to one another at distances of about 10^{-13} cm. The charge of every nucleon constantly changes. But the total number of protons remains constant (equal to Z), although we cannot say which nucleon is at a given moment charged and which is not. The forces between nucleons are transmitted by pions – their number in the nucleus is totally indeterminate; pions are constantly born and captured, and form what is briefly termed the field of nuclear forces.

This picture of the structure of the nucleus satisfies the taste of the most demanding critic. This picture leaves no place for new particles or new details, and it seemed that, having constructed this model, physicists could quiet down a bit.

But the reality proved to be much more complicated. After the discovery of pions, more and more new particles were constantly discovered in cosmic rays. The 'hunt' was especially fruitful at the beginning of the sixties; now the list contains more than a hundred of particles, and probably only the restricted energy of accelerators has somewhat slowed down the growth of this list. The position of a physicist is similar to that of an unlucky mechanic who has successfully taken a watch to pieces but, on putting it together, finds that he has many details left over and is in the dark as for their purposes. In spite of this the watch kept perfect time.

Having smashed the proton into pieces and discovered a tremendous variety of its constituents, physicists cannot comprehend the purposes of the vast amount of particles and their role in the physical processes of the microcosm. Before physicists were looking for missing parts necessary to confirm hypotheses; nowadays the attempts to understand mutual relationships between the plethora of experimental facts, which do not fit into the picture (apparently a primitive one) of the universe developed by the middle of the twentieth century, are much more troublesome.

Exponential Decay

Many of the particles we have discussed above undergo decay: pions decay into muons, neutrons transform into protons. Talking of decays, we use the term lifetime of a particle. Nowadays this characteristic became customary and seems quite natural; however, it is worthwhile to discuss it at some length to bring out one additional unusual property of the microcosm.

Suppose we have 1 milligram of radium. Each second approximately 4 billion radium nuclei are decayed transforming

into radon. But which of the nuclei have decayed? Can we have a glance at a nucleus and say how much time will elapse before this nucleus ceases to exist? As it happens, we cannot. We can only say that a certain fraction of radium nuclei decay during a certain time interval. More detailed information cannot be retrieved. The law of radioactive decay states: the decay reduces the number of nuclei per unit time by a number (denoted here by ΔN) proportional to the total number of nuclei

$$\Delta N = -\frac{1}{\tau} N$$

where the constant $1/\tau$ (often written as λ) characterizes a given nucleus and determines its rate of decay.

If we had N_0 nuclei at the initial moment of time, then the formulated law yields that at any other moment of time t the number of nuclei will be reduced and described by the formula

$$N = N_0 e^{-t/\tau}$$

This formula again includes the already familiar number e equal approximately to 2.72. The physical meaning of the characteristic τ is also clear from the formula: the number of nuclei decreases e times during the time τ. It can also be shown that τ is equal to the mean lifetime of the nucleus (about 2300 years for radium).

This decay law is very often encountered in science and in technical fields, and is called the exponential function (exponential function is a power function). We have met a relationship of this type while discussing the potential of nuclear forces. We can say, for instance, that the population of a country rises approximately exponentially – the population increment in most European countries is about 0.01 of the total population per year. The temperature of a hot kettle placed on the table also decreases approximately by the exponential law. The reason for this generality of relationship in dissimilar phenomena is more or less clear. The process controlling the details of the population growth is extremely complicated and involves a great number of various factors so that a meticulous description of the fate of each citizen of the country would be a task unthinkable and unnecessary. Actually this complicated system – and exactly owing to its complexity – is so averaged that we observe the law of mean population growth.

When a kettle cools down, the description of the process will also be too difficult if we try to find out how the slowing down of each molecule proceeds when it strikes the walls of the kettle. However, if we neglect the microscopic details of the process and

describe the state of the kettle by a single macroscopic (i. e. averaged) characteristic, viz. temperature, this quantity will behave in a simple manner. The exponential law is observed when we consider the behaviour of a system with a very high (ideally even infinite) number of degrees of freedom, and describe this behaviour by means of a single averaged parameter (number of particles, temperature).

From this point of view the exponential decay of the atomic nucleus may also be explained in terms of a large number of nucleons for which we know neither exact positions nor velocities. Their behaviour is so averaged that the decay becomes equally probable for any nucleus.

Exponential decay can also be looked upon from a different standpoint. In this type of decay the system completely forgets its previous history: if we collect the products of decay, we have no means at our disposal to find out which nuclei have decayed and when. Just as it is difficult to reconstruct the shape of a bottle from the tiny fragments it has broken into.

If the foregoing reasoning could be called an explanation of the exponential decay law, then the applicability of this law to elementary particles would seem strange. In reality we did not explain the law; and, strictly speaking, it cannot be proved if no assumptions are made. Nevertheless, the above explanations look plausible. But if it is so, then why should pions decay exponentially? In what sense can we say that a pion is a complex system and that a large number of degrees of freedom are involved in the decay? These questions are hard to answer. However, if we keep to the usual point of view, we have to assume that pions (and other elementary particles) are indeed extremely complicated systems, only this complexity will not be revealed to the observer unless he penetrates deep into the particle. And now we indeed know that the processes in elementary particles become increasingly more complicated with an increase in energy.

In this sense the physicists, as soon as the radioactive decay had been discovered, could suspect that the model of the microcosm should look very complex; only the perennial desire of natural scientists to seek simple laws in natural phenomena inspired them in their search for simple models. However, these models always proved to be mere steps in learning the truth and withstood only those tests, which did not touch upon too subtle details of the phenomenon. Only by resorting to simple models one can penetrate into the depths of the microcosm whose properties are as inexhaustible as those of the universe.

Baryon Charge

We said that our model of a nucleon is becoming more and more complicated. But complications involve new laws which control the violent processes inside the nucleon and make a proton a proton. No wonder that the nucleus acquires new properties, which before either went unnoticed or their significance was not realized. Now we want to discuss one of such properties — the baryon charge.

If a proton is regarded 'from afar', it will look like a dot. But if 'approached' very closely, it stops being an indivisible particle or a stationary structure. It should rather resemble a violent eddy in which pions are born and consumed. Apart from pions, nucleons and antinucleons are produced and decay, very close to (or rather inside) the entity we call the proton. What was a proton at one moment of time may at another moment turn virtually into a system of two protons and one antiproton:

$$p \rightarrow p + p + \bar{p}$$

The antiproton is negatively charged (as an electron) and its generation is obviously due to the condition that the net charge must not change, and any new generated proton must be compensated for by an antiproton.

The same rule will be observed in actual proton-proton collisions:

$$p + p \rightarrow p + p + p + \bar{p}$$

In this reaction a new proton is born 'paired' with an antiproton. The charge conservation law must hold in any case (this law is not subject to anything similar to the uncertainty principle).

We shall discover something new if we observe the birth not of a proton but of a neutron.

It is found that a proton-proton collision (or a neutron-proton, or a neutron-neutron collision) cannot generate the neutron alone though it is not forbidden by the requirements of the charge conservation law. Neither can an antineutron appear alone. Similarly to protons, neutrons are also born in pairs:

$$p + p \rightarrow p + p + n + \bar{n}$$

If energy is sufficiently high, several nucleons can be generated, each new nucleon being balanced by a new antinucleon in each case. A similar rule is observed in the reversed process, i. e. in the annihilation of an antinucleon. In a nucleon-nucleon collision both of the participants cannot disappear. The result

of this collision must be either the birth of new particles, or the nucleons will just fly off.

In a nucleon-antinucleon collision the particles can (and usually do) annihilate, i. e. disappear, leaving in their place pions, photons or something else.

The capability to annihilate in the collision with a nucleon is the fundamental, determining property of the antinucleon. This property distinguishes the zero-charged neutron from its equally zero-charged counterpart, antineutron.

If new nucleons are born in a reaction in which nucleons, pions, electrons or quanta participate, an equal number of antinucleons must be produced simultaneously.

When antinucleons were not yet known – and it was not too long ago, since antineutron was discovered only in 1956 – the law of conservation of the number of nucleons could be formulated as follows: no transformation in nature can change the number of nucleons, i. e. the number of nucleons in the universe is invariant; a proton may turn into a neutron; a neutron may transform into a proton – but the number of nucleons before a reaction must be equal to that at the end of the reaction.

After the discovery of antinucleons the situation seemed to grow more complicated. In many reactions the number of nucleons was not conserved any more: two nucleons appear instead of one (plus one antinucleon), four nucleons instead of two (plus two antinucleons), etc. Briefly, the law of conservation of the number of nucleons was no longer valid. But a new conservation law emerged to replace it.

Let us agree to count the particles in a rather special fashion. We shall count nucleons as usual: one, two, three, ... ; and each antinucleon we shall count backwards: minus one, minus two, ... It means that two antinucleons are taken for minus two particles, a nucleon and an antinucleon for zero particles, etc. With this manner of counting we find that the number of particles is conserved in all processes. We see that antiparticles indeed act as the opposites of particles. But such a terminology is rather irritating and should better be avoided.

You may recall that to count protons we can measure the charge of the system and divide it by the charge of one proton. This method of counting reminds a witty reply of an old herdsman: if you want to quickly count the number of sheep, count the number of feet and divide it by four. This method is really good for protons; it automatically gives the difference between the number of particles and that of antiparticles. But if the system

also includes neutrons, then its electric charge is not indicative of the number of constituent particles. To be always sure that the result is correct, let us take the following line. Let us introduce a new concept – the baryon charge* – and attribute the baryon charge of +1 to a neutron and a proton, and the baryon charge of −1 to an antineutron and an antiproton. Now, instead of conservation of the number of nucleons, we shall formulate the law of conservation of the baryon charge: in any transformation in nature the baryon charge is conserved.

This law appears rather arbitrary, but it reflects a fundamental property of atomic nuclei, viz. their stability. A slightest violation of this law would result in vanishing of protons or neutrons which would transform, for example, into positrons, neutrinos or mesons. Our very existence is due to the never-failing law of conservation of the baryon charge.

The law of conservation of the baryon charge is very similar in form to that of the electric charge: only such electric charges are found in nature which are integral multiples of the electron charge. Therefore, to say that the electric charge is conserved is equivalent of saying that the difference between the number of positively charged and negatively charged particles is conserved. Thus the charge takes on a new meaning: it becomes a distinctive characteristic from which we can determine the number of particles of distinct types.

The electric charge helps to count the number of charged particles. The baryon charge helps to count baryons. We should also add that the electric charge is zero for neutral particles, i. e. neutrons, pi-mesons, photons. The baryon charge is equal to zero for small-mass particles – electrons, neutrinos, and mesons.

So far we have mentioned among the particles possessing the baryon charge only the proton, the neutron and their antiparticles. But we shall get acquainted with the reactions in which protons and neutrons disappear; the conservation law of baryon charge remains firm and secure owing to the appearance of new particles.

The law of conservation of the baryon charge is one of the most thoroughly checked laws of nature.

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* This was first termed nucleon charge, but since now we know, besides nucleons, other particles similar to them (these will be discussed below) and which together with nucleons fall into the class of baryons, the charge was re-named baryon charge.

Mesons

Mesons, through which nucleons interact, behave quite differently from nucleons themselves. When two nucleons collide, as many mesons are born as the energy supply allows. For example:

$$p + n \rightarrow p + p + \pi^-$$

or

$$p + n \rightarrow p + p + \pi^- + \pi^0$$

or

$$p + n \rightarrow p + n + \pi^- + \pi^+, \text{ etc.}$$

Neither these nor other reactions bear any traces of any conservation law for mesons, so no mesonic charge is introduced for them. Therefore in contrast to baryons mesons can decay converting into other particles. Thus a positive pion (pi-meson) is transformed into a positive muon (mu-meson) and a neutrino.

A negative pion decays into a negative meson and an antineutrino. The mean lifetime of charged pions is 2×10^{-8} s.

The third pion, π^0-meson, is neutral; it should be expected to decay in a similar way.

The search for the neutral pion continued for a long time, and even a name was specially devised: neutretto. However since nature was proved to contain no neutral muon, the suspicion aroused that there was nothing for the π^0-meson to decay into.

Nevertheless π^0 decays and even much quicker than its charged counterparts. It lives only for 8×10^{-17} s and decays into two photons:

$$\pi^0 \rightarrow \gamma + \gamma$$

(This is the place where one should feel amazed by the ingenuity of experimentors. Neither a neutral pion nor photons leave any traces on photographic plates or in chambers. Photons are recorded because they are converted into electron-positron pairs. By observing two simultaneously generated pairs, measuring their momenta and checking the conclusions by the laws of energy and momentum conservation we can make sure that the decay of a neutral pion did take place.)

The decay of π^0 has another interesting side to it. Usually photons are emitted when charged particles are decelerated. For instance, decelerated electrons emit X-rays, i. e. photons with a comparatively low energy. Elementary particles emit photons when their charge changes; thus a π^--meson scattered on a proton may decay into a π^0-meson, thereby producing photons. When a π^0-meson decays, photons are emitted in the process of complete disappearance of the particle, of its, so to speak, transformation

into vacuum. The π^0-meson behaves as if it were a proton-antiproton pair which in turn also disappears completely. This analogy has even stimulated theorists to try and describe the π^0-meson as a bound proton-antiproton pair. However, these attempts failed. We shall see that the interest in constructing certain particles as combinations of other ones was again given new life when the idea of quarks had been suggested.

The pion family is not the only company of mesons. But before discussing other representatives of this group it will be useful to return to baryons and first follow the proliferation of this family.

Excited Nucleons

Everything looked simple and attractive when the microcosm model contained only two nucleons surrounded by the cloud of pions. Each particle had its 'responsibilities', and nothing could be either added or removed.

However, the question about the structure of the proton was left unanswered. If we consider the proton to be a complicated system, i. e. with various processes taking place in it, we cannot explain why the mass does not change.

As in the case of the hydrogen atom, this system must have high-mass excited states. We can even estimate that masses of such excited states must exceed that of the proton by approximately the mass of the pion, i. e. by 140 MeV. Quite a few scientists believed that for some reasons such states would not be observed; it was nice to consider the work almost completed. But when it became possible to produce the beams of fast pions in accelerators, it became clear that the work remaining to be done stretches for many years ahead.

As usual, the beginning seemed to be insignificant: the experiments with pions scattering by nucleons indicated that when the energy of impinging pions approached 160 MeV, the probability of scattering steeply increased. As the energy increased, this probability rose, reached maximum and then diminished. If we plot the probability of scattering as a function of the pion energy, we shall obtain the resonance curve. Scattering is characterized by a special parameter called the effective cross section of scattering (or simply cross section). Imagine that a nucleon is bombarded by a beam of pions so that each square centimetre of the beam cross section is crossed by 1 pion per second. If each second a σ of pions change the direction of flight (because of collisions with the nucleon), then σ is the effective cross section (the nucleon acts

as a body of certain size, opaque to pions). Cross sections are usually measured in barns: 1 barn = 10^{-24} cm^2.

What is signified by the maximum on the scattering curve? It implies that at the pion energy of about 160 MeV the pion, having collided with the nucleon, does not immediately fly away but spends some time in its vicinity. The pion makes several turns around the nucleon. The time the pion spends on this orbiting (it may be called the delay time) is determined from the width of the resonance curve.

To describe the resonance we can use the following analogy. Let us compare a radio receiver, which is tuned to a certain energy (or frequency) of radio waves, to a proton. The receiver absorbs the radio wave, transforming it into sound, while a proton does not absorb pions, letting them go. However, a proton can also absorb π^- or π^0, it only must release the energy excess by emitting, for instance, a photon. In such reactions nucleons function almost like TV sets transforming 'pion waves' into light. But by turning the controls we can tune the receiver to various wavelengths, i. e. to various broadcasting stations. The proton is tuned by nature once and for all: it is good at absorbing only specific waves (pions), it has no control knobs which we could turn. Resonances reveal a fundamental property of quantum systems, and nucleons possess them just as atoms and molecules do.

The discovered resonance state of the proton-pion system can be described as the excited state of the nucleon. Such excited states are a familiar fact for atoms. An excited atom emits photons. Photons, impinging on an atom, change it to an excited state; after some delay, the atom re-emits the photon; this is the well-known resonance scattering of light by atoms.

The excited state of the nucleon with the mass of about 1236 MeV (proton mass + pion mass + pion kinetic energy) is formed as a result of different reactions:

$$\left.\begin{array}{l} p + \pi^+ \\ p + \pi^0 \\ n + \pi^+ \\ n + \pi^0 \\ p + \pi^- \\ n + \pi^- \end{array}\right\} \rightarrow N^*$$

In these reactions the charge of the excited state can vary: from +2 in the first reaction to −1 in the last. The excited nucleon is said to have four charged states.

The four charged states of nucleons, shown above, are denoted, respectively, as N^*_{++}, N^*_{+}, N^*_{0}, and N^*_{-}, and are said to be almost

indistinguishable (by analogy with the two states of the nucleon).

After the discovery of the first excited state it became clear that the very concept of the elementary particle underwent a substantial modification. Nature has revealed the entities which are very short-lived (10^{-23}-10^{-22} s), but nonetheless have an almost definite mass (with the spread less than 10%), quite a definite spin, and baryon charge. And there is every argument in favour of regarding these entities as particles. These particles are called *resonances* to remind one of the resonance nature of the curve through which their existence was detected.

The only justification for the term resonance is in the fact that their lifetimes are specified by an isolated interval. We have already encountered a lifetime of 10^{-16} s, i. e. the lifetime of the neutral pion. Further below we shall meet another meson – η-meson (eta-meson, or eton) – which lives for approximately 10^{-19} s. After the eta-meson there is a gap in the table of lifetimes: there are neither particles nor resonances (whatever the label) down to a lifetime of 10^{-22} s.* Therefore we can refer to all particles, living not less than the eta-meson, as particles, and to those whose lifetime is less than 10^{-22} s, which corresponds to only a dozen of turns in the almost bound state, as resonances. Of course, this condition is somewhat arbitrary.

No matter how we decided to call the new states – particles, resonances or something else – they have taught us a good lesson. But when we question nature we must be ready to get a much more complicated reply than we expected. Once it was established that the nucleon's structure is complicated, it stopped being an elementary particle in the old sense of the word and turned into a system with the whole spectrum of distinct states. This spectrum included, among others, resonances which appeared only for a short instant. But scientists got quickly used to it, and the situation quieted down again. But the lull was brief.

Hyperons

Each new discovery brings with it new terms. Unusual at the beginning, they grate upon the ear, but then somehow penetrate into our language. The discoveries in the physics of elementary particles also introduced new terms.

The beginning of the fifties of the new century was marked by the boom of discoveries of new particles, and they had to be

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* This was written some time ago. Now physicists have discovered a new particle with a lifetime of about 10^{-20} s. The gap is almost closed. See p. 99.

labelled. In a hurry the names were simply chosen among letters. In this way Λ-particle, Σ-particle, etc. appeared. Not to get lost in this maze, the whole family was assigned a family name: these new particles were termed *hyperons.*

Not all of the excited states of nucleons are so short-lived as resonances. By observing the events in pion-nucleon collisions, physicists have singled out an essentially new phenomenon.

In some of the collisions the pion disappeared and a new meson, named *K*-meson, or kaon, was born in its place. In the process the nucleon was converted into a new particle. This new particle, which, like the nucleon, was a baryon, lived much longer than ordinary resonances, about 10^{-10} s. When it decayed, a pion and a nucleon re-appeared – the initial situation was restored, with the addition of the *K*-meson.

By nuclear time standards a lifetime of 10^{-10} s is very long, and our new baryons looked almost stable. During their lifetime they can travel the distance of 1-2 cm so that, in contrast to resonances, their tracks can be recorded. Such baryons were first observed not in accelerators but in cosmic rays. However, their properties became well known only after these particles had been reliably produced in the laboratory conditions.

Let us try first of all to explain why they are referred to baryons. We said that nature conserves the baryon charge. But in the pion-nucleon collision the nucleon has disappeared. The newly-born *K*-meson has zero baryon charge since it decays into pions. Hence the baryon charge could only pass to the new particle, and the whole process can be described as:

$$p + \pi \rightarrow H + K$$

(baryon charge $1 + 0 = 1 + 0$). The letter H denotes the new particle, hyperon.

Hyperons were found to be of different types; correspondingly, kaons may carry different charges. The first to be discovered were the processes of the following type:

$$p + \pi^- \rightarrow \Lambda^0 + K^0$$
$$p + \pi^+ \rightarrow \Sigma^+ + K^+$$
$$n + \pi^- \rightarrow \Sigma^- + K^0$$

Two types of hyperons are born in these processes: lamda-zero hyperon with a mass of 1116 MeV and two types of sigma-hyperons with almost identical masses (Σ^+ with a mass of 1190 MeV and

Σ^- with a mass of 1197 MeV). These hyperons mostly* decay as follows:

$$\begin{aligned} \Sigma^+ &\to p + \pi^0 \\ &\to n + \pi^+ \quad \text{(lifetime } 0.8 \times 10^{-10} \text{ s)} \\ \Sigma^- &\to n + \pi^- \quad \text{(lifetime } 1.5 \times 10^{-10} \text{ s)} \\ \Lambda^0 &\to n + \pi^0 \quad \text{(lifetime } 2.5 \times 10^{-10} \text{ s)} \end{aligned}$$

One more hyperon was obviously lacking from these reactions. The theory urgently required its existence; and indeed, the neutral Σ^0-hyperon was also discovered, and it, too, was produced in pion-nucleon interactions. The mass of Σ^0 proved to be close to those of Σ^+ and Σ^- (1192 MeV). But its decay was quite dissimilar to those of its charged counterparts

$$\Sigma^0 \to \Lambda^0 + \gamma \quad \text{(lifetime } 10^{-14} \text{ s or less)}$$

But this was not yet the end. Other hyperons were discovered, besides Σ- and Λ-hyperons. The properties of two xi-hyperons, Ξ^- and Ξ^0, which decayed by the reactions

$$\begin{aligned} \Xi^- &\to \Lambda^0 + \pi^- \quad \text{(lifetime } 1.7 \times 10^{-10} \text{ s)} \\ \Xi^0 &\to \Lambda^0 + \pi^0 \quad \text{(lifetime } 3.0 \times 10^{-10} \text{ s)} \end{aligned}$$

were considered by physicists to be very unusual.

The unusual about them was, firstly, that xi-hyperons did not decay directly into nucleons, but had to go through the stage of turning into a lambda-hyperon.

Secondly, it appeared strange that the xi-hyperon had no positively charged partner. Xi-hyperons resembled a pair of nucleons and not a trio of sigma-hyperons. The masses of both xi's proved to be very close (1321 MeV for xi-minus and 1315 MeV for xi-zero).

But the most striking was the very process of production of xi-hyperons. They were born together with two kaons. For instance, as

$$\begin{aligned} p + \pi^- &\to \Xi^0 + K^0 + K^0 \\ n + \pi^0 &\to \Xi^- + K^+ + K^0 \end{aligned}$$

The last representative of the hyperon family caused a world-scale sensation (we shall explain the reason later). This was the Ω^--hyperon (mass – 1672 MeV, lifetime – 1×10^{-10} s).

* We say 'mostly' because sometimes hyperons decayed as radioactive nuclei with emission of an electron.

The omega-hyperon has no partners. Its birth is especially surprising because it is accompanied by three kaons:

$$p + \pi^- \rightarrow \Omega^- + K^0 + K^0 + K^+$$

Now we have enumerated all the hyperons. There were eight of them, all originating from nucleons. Not a trace remains of the simple picture of the nucleon structure. The picture becomes more and more complicated, and the number of questions increases rapidly. But the jinn is out of the bottle, and we have to answer for the consequences.

Excited Hyperons

Similarly to nucleons, sigma-, lambda-, and xi-hyperons were found to possess many excited states. Physicists compile whole tables of such states, and their discussion becomes dull for non-specialists. Nevertheless, we list some of them in the table on p. 90. It combines hyperons from two families of the octet (or a group of eight) and of the decuplet (or the decade). We shall later explain why they are called in this way. Now we only want to emphasize that the omega-meson heads the family, the decade, although it lives much longer than other members of this family.

Ω^--Hyperon and Its Descendants

The birth and fate of the Ω^--hyperon are so interesting that it is worthwhile to spend some time discussing them.

Although we have said that Ω^- is born accompanied by three kaons, this statement is not quite correct: one of the kaons usually plays its part at the beginning of the reaction (on the left-hand side of the formula). The reaction described below was observed in the beam of negative kaons:

$$K^- + p \rightarrow \Omega^- + K^+ + K^0$$

Each kaon decays into two pions. Ω^- emits a pion and converts into Ξ^0; this is already the third generation. Xi-hyperon, in its turn, decays into a Λ^0-hyperon and a neutral pion. As we know, the neutral pion decays into two photons (the fifth generation). And finally, in the sixth generation each of the photons produces an electron-positron pair. And all the six generations with the corresponding branches were observed on one photograph!

Three hundred thousand photographic plates had to be scanned to pick out one such unique photograph. Eight of the plates

contained tracks of Ω^--hyperons. But the observed number of its descendants, viz. Λ^0-hyperons, was already 6000.

The description of life of six human generations cannot be squeezed into a single volume, no matter how bulky. In the microcosm a single photographic plate can demonstrate the life of six generations of particles! Such a photograph was hard to obtain. To observe the anti-Ω^--hyperon was even more difficult. But finally even this hyperon was found. Now we can say that all antibaryons have been discovered. But it took 15 years!

Strangeness

Let us begin to decipher little by little the processes of birth and decay of hyperons. Why do hyperons live so long (as compared to resonances)? Unfortunately, we cannot yet answer this fundamental question. Nobody can. Nevertheless, we can observe certain regularities in decays and some order in the picture which at first seemed chaotic.

To visualize this order we shall assume a lifetime of 10^{-10} s to be very big and thus consider these particles to be stable, i. e. not decaying at all.

Then, analyzing the system of stable hyperons, we would establish a new conservation law similar to that of the baryon charge. This new law could look as follows: if we collect into one group (let us call it group A) all hyperons and the K^--meson, and into the second group (group B) all antihyperons (we know that they exist and were observed, all of them) and also K^+- and K^0-mesons, then, after analyzing the above reactions, we can say that the difference between the number of the B-group particles and that of the A-group particles remains constant.

However, this is not quite true. Group A includes one kaon K^-, while group B two kaons, K^+ and K^0. The positive kaon can be regarded as the antiparticle to K^-; this point of view is born out rather well by the experiment. But then we must find the antiparticle to the neutral kaon $\bar{K}^0$. The neutral antikaon really exists and, at least in principle, K^0 and $\bar{K}^0$ can turn, for instance, into a proton + antiproton pair. The $K^0\bar{K}^0$ pair may be born in a nucleon-nucleon collision.

If we had only kaons (stable within the agreed time scale), then the law of conservation of the kaon charge (let us introduce this term too!) would hold for them: the number of kaons minus the number of antikaons is conserved. Pions are not subject to any similar law (neither separately nor together with nucleons);

therefore the properties of kaons are much more interesting than those of pions.

Now we easily modify our law of conservation of the difference between groups A and B. We have to attribute to hyperons the negative kaon charge, and to antihyperons the positive kaon charge. Then we can say that the kaon charge is conserved.

The term kaon charge, which we invented here, is very convenient. However, there is a very convincing argument against it: this charge has already been labelled. Being fascinated by the properties of hyperons, Gell-Mann gave the name *strangeness* (S) to what we were inclined to call the kaon charge. Naturally, we shall use this term accepted by everybody.

The strangeness of particles is as follows:

$S = 0$ for nucleons, antinucleons, and pions
$S = +1$ for $\bar{\Lambda}$-, $\bar{\Sigma}$-hyperons, and for K^+, K^0
$S = -1$ for Λ-, Σ-hyperons, and for K^-, $\bar{K}^0$
$S = +2$ for $\bar{\Xi}$-hyperons
$S = -2$ for Ξ-hyperons
$S = +3$ for $\bar{\Omega}$-hyperons
$S = -3$ for Ω-hyperons

Strangeness is often replaced by another, very similar, characteristic, viz. hypercharge. *Hypercharge* Y is the sum of strangeness S and baryon charge B: $Y = S + B$. Therefore the hypercharges of baryons and mesons are:

$Y = 0$ for Σ, Λ, $\bar{\Sigma}$, $\bar{\Lambda}$, and pions
$Y = +1$ for nucleons, $\bar{\Xi}$, K^+, and K^0
$Y = -1$ for antinucleons, Ξ, K^-, and $\bar{K}^0$
$Y = +2$ for $\bar{\Omega}$
$Y = -2$ for Ω

Below are given some characteristics of baryons:

Octet (MeV)	Decuplet (MeV)	Strangeness	Hypercharge
–	Ω 1670	−3	−2
Ξ 1300	Ξ^* 1530	−2	−1
Σ, Λ 1150	Σ^* 1380	−1	0
N 940	N^* 1230	0	1

The law of strangeness (or hypercharge) conservation makes it possible to describe all reactions of birth and decay of baryons.

For instance,

$$p + \pi^- \to \Lambda^0 + \pi^0$$

is forbidden since the strangeness of the right-hand side is -1. The reactions

$$\pi^- + p \to \Omega^- + K^0 + K^+ + K^0$$

and

$$K^- + p \to \Omega^- + K^+ + K^0$$

satisfy the new law, but the reaction

$$\pi^- + p \to \Omega^- + K^+ + \bar{K}^0 + \bar{K}^0$$

violates it. (Although from the point of view of the baryon-charge and electric-charge conservation laws this reaction is possible.)

Thus, having invented a new law, we are able to explain all reactions. But can we explain the law itself, can we relate the strangeness to some other, more comprehensible (or more customary) properties? In trying to achieve this, Gell-Mann and Zweig have invented new particles, viz. quarks. It seems that nature contains no quarks, but their discussion is worthwhile.

Long Lifetime of Ω

Now we can answer the question as to why the omega-hyperon is so long-lived ($\sim 10^{-10}$ s) while its partners in the decuplet decay almost instantaneously. Let us look at the table of baryons. We see that all excited baryons, i. e. resonances, N^*, Σ^*, and Ξ^*, can without altering strangeness emit a pion and transfer into ground states N, Σ, and Ξ, i. e. transform into the baryons from the octet. The decays with the strangeness conserved proceed very rapidly. However, the octet includes no baryon with a strangeness -3, i. e. with the strangeness possessed by the omega-hyperon. Hence, the omega-hyperon cannot decay in the same way as its partners in the decuplet follow.

To decay with the strangeness conserved, the omega-hyperon were to emit a kaon since each kaon carries away one unity of strangeness. But checking with the table on p. 90 and recalling that the kaon mass is about 500 MeV, we see that the decays $\Omega \to \Xi^- + \bar{K}^0$ or $\Omega \to \Sigma^- + K^0 + K^0$ or, finally, $\Omega \to n + \bar{K}^- + \bar{K}^0 + \bar{K}^0$, which do not contradict the strangeness conservation, cannot take place because there is not enough energy: the mass of the omega-hyperon is too small. Therefore the only way left for the Ω-hyperon to decay is by violating the strangeness conserva-

tion law. We are again inclined to ask for the physical reasons that impede such transformations. The answer to this question must be sought in the yet unknown complexities of the structure of the strange particles and in the mechanism of kaons' production. But whether this question can be answered in terms of modern quantum mechanics or it is one of the forbidden questions, we do not yet know. It is possible that the complexity of the microcosm will call for the development of new theoretical methods altering the notions and images we are accustomed to.

Quarks

About a decade ago a simple and comprehensible idea was suggested that all elementary particles consist of three most elementary particles, quarks; the impression was that all problems were satisfactorily solved.

But to make ends meet, quarks had to be assigned only one unusual property: their electric and baryon charges had to be integral multiples of one third. This picture left no place for neutral, zero-charged quarks.

The quarks were denoted by the letters d, u, and s, and were referred to as d-quark, u-quark, and s-quark. The first is the down-quark, which decreases the charge, the second is the up-quark, which increases the charge, and the last is the strange quark. Quark charges were selected in the following way:

Quarks	d	u	s
Electric charge	$-1/3$	$+2/3$	$-1/3$
Baryon charge	$+1/3$	$+1/3$	$+1/3$
Strangeness	0	0	-1
Hypercharge	$+1/3$	$+1/3$	$-2/3$

Quarks, as all other particles, have their corresponding antiparticles, with the following charges:

Antiquarks	$\bar{d}$	$\bar{u}$	$\bar{s}$
Electric charge	$+1/3$	$-2/3$	$+1/3$
Baryon charge	$-1/3$	$-1/3$	$-1/3$
Strangeness	0	0	$+1$
Hypercharge	$-1/3$	$-1/3$	$+2/3$

There is nothing strange in the concept of a fractional charge. There are no profound arguments demanding the charge of the proton (or of the electron) to be minimal. All charges in nature still remain integral multiples of the elementary charge, only the unit of measuring it became three times smaller. Thus this feature causes no objections.

The tables demonstrate that only the s-quark and the $\bar{s}$-antiquark possess strangeness. The two other quarks, d and u, have zero strangeness. The proton and neutron are made of these two quarks.

Moreover, we deduce from the table that the baryon charge equal to unity can be accumulated only if at least three quarks are selected. The proper selection, producing the necessary net charge, is easily achieved. It only remains to fit the spin, i. e. the inherent momentum of the nucleon's motion.

The quark spin is assumed to be equal to one half, just as that of the nucleon. When we start to construct nucleons out of quarks, as of blocks, the three quarks must compensate their spins in such a way that the net spin should also be equal to one half. Therefore we can construct a proton by taking three quarks

$$u + u + d = p$$

Checking with the table we obtain 1 for the net charge of the proton.

Obviously, a neutron is obtained as

$$u + d + d = n$$

It is logical to ask what the result of taking three u-quarks or three d-quarks should be. As it happens, we obtain the resonance states of the nucleon we have discussed above. We shall return to this later. Let us replace d-quarks in the above triads by s-quarks. We obtain baryons with the strangeness of, respectively, minus two and minus one. Baryons in which u-quarks are replaced by s-quarks will have the same strangeness.

Two of these baryons will lead to Ξ-hyperons:

$$s + s + d = \Xi^-$$

$$u + s + s = \Xi^0$$

If we replace only one quark, we shall obtain two combinations from the proton. One of them (d is replaced by s) is the Σ^+-hyperon:

$$u + u + s = \Sigma^+$$

Another one is similar to both Λ^0 and Σ^0 (u is replaced by s):

$$u + s + d = \Sigma^0 \text{ or } \Lambda^0$$

The neutron also yields two combinations:

$$s + d + d = \Sigma^-$$
$$u + s + d = \Sigma^0 \text{ or } \Lambda^0$$

Here, though, we notice a difficulty: we cannot indicate any difference in the structures of the Σ^0- and Λ^0-hyperons.

In reality (and this can be related only by utilizing the language of quantum mechanics) both Σ^0 and Λ^0 can be obtained from either a proton or a neutron. Both hyperons, Λ^0 and Σ^0, are very much alike, the only difference being that the Σ^0-hyperon is included into the triad of Σ-hyperons (Σ-hyperons form a triplet) while Λ^0 exists alone (Λ^0-hyperon is a singlet). In fact it is not odd that this subtle difference is not described by a primitive language.

Thus, eight hyperons proved to be constructable out of the three quarks. Antihyperons are just as easily constructed: one only has to replace quarks by antiquarks.

The scheme of mesons differs from that of baryons in two points: firstly, it includes both particles and antiparticles, and, secondly, it presents greater difficulties in attempts to explain the structure of neutral mesons π^0 and η. The neutral pion is partially composed of $u + \bar{u}$ and partially of $d + \bar{d}$. The neutral eta-meson (we shall discuss it later) includes, in addition, a fraction of $s + \bar{s}$. These words are hardly understandable, but if we consider the quark hypothesis seriously, we can say that half of its short life a neutral pion exists as a bound $u + \bar{u}$ pair, and another half as a $d + \bar{d}$ pair. A neutral eton divides its time into three parts and lives as a $u + \bar{u}$ pair, a $d + \bar{d}$ pair, and as an $s + \bar{s}$ pair.

Other particles can also be constructed by combining different quarks; this simple theory interprets an unexpectedly large number of phenomena. This gives rise to some doubt whether we were right in denying the validity of the question as to what the proton consists of. The answer depends upon whether quarks do or do not exist in nature.

The Baryon Decuplet

It seemed that quarks have brought with them solutions to a number of problems. The only remaining task was to find them, and the answer to the question about the components of elemen-

tary particles would be in our hands. But even the yet undiscovered quarks permitted new predictions to be made. The most sensational among them was the predicted discovery of the Ω-hyperon whose decay was mentioned above.

It is quite easy to realize how this discovery was made. It will be sufficient to play a sort of game of patience in which triads of quarks play the part of combinations. Laying out this patience we follow some profound law of nature whose meaning still remains obscure.

We shall lay out the decuplet patience in a triangular manner. The base is formed by triads without *s*-quarks. These are baryons, namely, excited states of the nucleon (designated N^*_{++}, N^*_{+}, N^*_{0}, and N^*_{-} with charges equal to $+2$, $+1$, 0, and -1, respectively).

The charge $+2$ signifies that the baryon (which in fact is not a particle but a resonance) is generated in proton collisions: since a π^--meson plus a neutron make up the most negative system, there can be no baryon with the charge -2 (this will make the antibaryon: π^- + antiproton).

Into the next row we put the excited Σ-hyperons; there are three of them with charges $+1$, 0, and -1. Each of them includes one *s*-quark. This means that for Σ's the strangeness is $S = -1$ (and the hypercharge $Y = 0$).

Above them we place two excited Ξ-hyperons with charges 0 and -1. They incorporate two *s*-quarks each and hence have the strangeness $S = -2$ ($Y = -1$).

The triangle is topped by the Ω-hyperon consisting of three *s*-quarks. This hyperon lives about 10^{-10} s, and in the microcosm time scale it can be regarded stable. We have already explained why this could happen, i. e. why the Ω^--hyperon is the only one in the whole decuplet to be observable in a free state (during its lifetime it travels about 1-2 cm).

As we know, the number of *s*-quarks manifests itself in the value of strangeness. We can calculate the strangeness for each row if we recall that it is equal to 0 for the *d*- and *u*-quarks and to -1 for the *s*-quark.

Let us look more attentively at the decuplet we have laid out. The particles, i. e. resonances, arranged in one row, have approximately the same masses. For example, the mass of N^*_{++} is equal to 1236 MeV and that of N^*_0 is only a few MeV greater. Naturally, the masses of resonances in different rows are not identical. The Σ^*_+ mass is greater than that of N^*_{++} by 146 MeV, and the Ξ^*_0 mass is greater than that of Σ^*_+ by 147 MeV.

This regularity had been noticed before the Ω-hyperon was

discovered. It so neatly fitted a simple (so simple that it looked primitive) theoretical scheme that a prediction was made about the existence of one more, the tenth, baryon with the mass exceeding that observed at the preceding stage by 145 MeV: 1529 + 145 = 1674. The reader can imagine how surprised everybody was when the prediction proved correct. Its only justification was the completion of the patience. Few believed in such arguments. But when the Ω-meson was recorded, the hope appeared that we had really discovered the most profound secrets of nature and that soon the microcosm would open up to us in all its majestic simplicity. However, no new patience was invented.

Do Quarks Exist?

First of all physicists rushed to search for quarks. We know particles tracked down by physicists even when they were equipped with much less information than in the case of quarks. From the standpoint of a thriller nearly everything was known about the criminal. Its charge, strangeness, and spin were known. The only doubtful quantity was its mass, although it was clear that quark cannot be lighter than one third of the proton mass (313 MeV). Indeed, if it were lighter than 1/3 of the proton mass, the proton would just break up into three quarks! The search was thorough: quarks were looked for in the atmosphere and in the ocean, attempts were undertaken to produce quarks in accelerators and to identify them in cosmic rays. But up till now nobody has succeeded in detecting even a single quark. The Serpukhov accelerator was used in the search for quarks; and again they were not found. A quark would be detected even if it were several times more massive than a nucleon and so strongly bound in the nucleons that nearly all of its mass were lost. But no quarks were detected. An incomprehensible law of nature stating that all charges must be integral multiples of the electron charge stands as firmly as before. The scheme which made it possible to make predictions was not confirmed in its most essential point.

The nucleon consists of three quarks, but the quarks themselves do not exist in nature. It is still possible that after a better search quarks will be finally found (by means of a large accelerator, for example). But is the present-day situation really so illogical? What if quarks do not exist? Should we discard the theory which so excellently describes a number of facts? (A rather large number of facts described by the quark hypothesis has been accumulated.)

It so happens that there is no need to give up this theory. The theory operates quite well with the quark model describing the properties of numerous particles, but it by no means leads to the conclusion that quarks are bound to exist in the free state.

Moreover, if quarks were indeed discovered, a new question would arise as to what quarks consist of. But if it were established that a proton could be broken into three quarks, then the problem of the quark structure would be even more complicated.

The fundamental problem would be found then in the quark-to-quark interactions: By what type of quanta quarks exchange, and why the interaction between them is so strong. In this sense the quark hypothesis merely shifts all problems concerning the properties of nucleons a step lower and in the long run does not facilitate the process of understanding them.

Already the structure of the nucleus is quite different from that of the atom. In all likelihood we just have no right to picture the nucleon as a nucleus made up of quarks: there is no place for similarity in nature, and it never reproduces the properties of large systems on a small scale. From this point of view the story of quarks is very instructive: the description of the criminal was known to the last detail, only it happened to be invented by the detective himself. And yet, could it be possible that this detective story is not yet over? Isn't there another thread we must keep to in order to finally get to the quarks?

A funny thing is that while the quark search is going on, a discussion continues about the meaning of the very word quark. The name for the hypothetical particles was extracted from James Joyce's *Finnegan's Wake* in which wild geese circle over a ship and cry out: 'Three quarks for Mister Mark.' A quark here is simply an imitation of goose cackle. Even more peculiar is the fact that Goethe used this word in *Faust*. In the prologue to the first part Mephistopheles says that man is always poking his nose into trash, which in German sounds as 'In jedem Quark begräbt er seine Nase.' But the German 'Quark' means at the same time 'curds', so that one encounters in shopwindows of dairies the announcement 'We buy curds' ('Wir brauchen Quark').

Future will show whether physicists really need quarks or Mephistopheles was right... .

ρ-Meson

We promised not to engage in the lengthy enumeration of the particles. However, it is worthwhile to devote some time to the

particles that are called truly neutral. In the beginning we knew only one sort of charge, viz. electric charge. The particles were classified into charged and neutral. But then it was found that even if a particle, neutron for instance, has zero electric charge, it has nevertheless a counterpart with opposite properties, viz. antineutron. An additional type of charge, baryon charge, was introduced to mark the distinction between neutrons and antineutrons. The baryon charge of the neutron is $+1$, and in this sense the neutron cannot be considered neutral. How then to define the neutral particle? It would be most logical to define the neutral particle as one which has no antiparticle. More precisely, we shall call a particle truly neutral if it coincides with its antiparticle.

The most typical representative of the absolutely neutral particles is the photon. Photons are equally emitted by both electrons and positrons, and their generation is not subject to any conservation law for the number of particles. To express it briefly, we can say that photons interact with antiparticles in exactly the same way as with particles.

Along with the photon, the neutral pion is another absolutely neutral particle, it also has no charges at all.

Eta-meson is also absolutely neutral. For example, it decays as

$$\eta \to \pi^+ + \pi^- + \pi^0$$

The particles on the right-hand side are absolutely neutral: replace pions by their antiparticles and it will not change anything.

Two more absolutely neutral mesons are similar to the photon. As photons, they possess polarization, but in contrast to the photon they have non-zero rest masses. These are ω-meson with a mass 784 MeV and ρ-meson with a mass 765 MeV.

The first of them (omega-meson) decays into three pions ($\omega \to \pi^+ + \pi^- + \pi^0$), and the second (rho-meson) decays into two pions ($\rho \to \pi^+ + \pi^-$).

Quantum characteristics of the rho-meson are similar to those of the photon, with the exception of the large rest mass. It seems to play the role of an intermediary in the processes of interaction between nucleons and the electromagnetic field. Generally speaking, it is one of the very few mesons that have certain duties in the microcosm (as pions and kaons).

Let us mention in passing that along with the neutral rho-meson there exist also two charged ones (with approximately the same mass), ρ^+- and ρ^--mesons, but we shall not discuss them.

The ρ^--meson has revealed itself most effectively in colliding

counter beams of electrons and positrons. Such experiments were conducted in Novosibirsk and in France. When the total energy of a positron and an electron reached the level corresponding to the rest mass of the rho-meson, a sharp resonance peak was observed in the scattering intensity curve. The resonance in the curve signifies that in this range scattering proceeds in two stages: a positron and an electron are converted into a neutral ρ-meson, which then decays back into the pair. Physicists say that ρ-meson dominates this process.

There is every reason to believe that the birth of the ρ-meson proceeds in such a way that first of all a photon is generated, which immediately transforms into the neutral ρ-meson. The analogy between the ρ-meson and the quantum is one of the most beautiful phenomena in the microcosm; its significance is not yet fully understood. And the ρ-meson is only the first member of a family of neutral vector mesons ω, ρ, φ, and ψ. What are they for?

Fall of 1974. New Problems

In November 1974 a new family of particles burst out of the accelerators. This time they were discovered in collisions of protons and beryllium nuclei in Brookhaven accelerator, and of electron and positron beams in Stanford. (The Stanford machine which gave birth to these particles is called SPEAR – for Storage Positron-Electron Accelerator Ring.) In January 1975 we knew three members of the new family. They are called ψ-particles (in Brookhaven they were christened *J*-particles): ψ (3105), ψ (3695), and ψ (4100). The masses of these particles are given in brackets. All the three particles are more than three times heavier than the proton. All of them decay into (e^+e^-)-pairs and hadrons: protons, antiprotons, and different mesons.

The ψ-family strongly differs from other neutral vector mesons by the unexpectedly long life of two of the ψ's. The lifetime of ψ (3105) and ψ (3695) is about 10^{-20} s, which corresponds to a line width Γ of about 100 keV. The third one, ψ (4100), has 'usual' lifetime, viz. almost 1000 times longer (Γ is of an order of 100-150 MeV). By the way, this ψ may be responsible for the large probability of (e^+e^-)-pair production which we have mentioned above. We are forced to conclude that some unknown factor prevents the decay of two ψ's.

The way of reasoning is as follows: there exists a fourth

kind of quark, let us call it c-quark (from the word charm*), and ψ is composed of c and $\bar{c}$. The transformation of c-quark into any of the 'old' three quarks is almost forbidden.

The third ψ is so heavy that it has sufficient energy, that is Mc^2 is sufficiently great to decay into two 'charmed' mesons (let us call then D and $\bar{D}$), which are built of c's (or $\bar{c}$'s) and of u and d (or $\bar{u}$ and $\bar{d}$). Thus a new game 'Find the D's' is open.

But we shall stop here. Maybe nature is revealing to us one of its most exciting mysteries.

Weak Interactions

Many physical phenomena, especially those in the microcosm, are frequently considered in the beginning to be rather insignificant and hardly very interesting. But once we analyze them more profoundly, the picture becomes exciting and essential.

The neutron is in many ways similar to the proton. But in contrast to it neutrons decay:

$$n \rightarrow p + e^- + \bar{\nu}$$

The lifetime of the neutron is tremendously long – about 1000 seconds. The interaction which results in so infrequent decays is evidently very weak, and it would be natural to expect that it is not related to any profound problems.

However, weak interactions play a possibly important part in the structure of our world. In any case, the phenomena discovered in these rare decays proved to be extremely interesting.

The difference between the decay of a neutron and the generation of a quantum or a pion is seen first of all in the fact that simultaneously two particles are emitted: an antineutrino and an electron.

In theory this leads to an essentially new consequence. While in electrodynamics the energy of interaction is equal to the product of current by the vector potential of the electromagnetic field, the respective energy in the case of weak interaction is proportional to the product of current by current: electron current by baryon current.** The constant characterizing the strength of interac-

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* It may be best to refer to Sir James Barry saying that if one has it (charm), he doesn't need anything else; but if he doesn't, it doesn't matter what else he has.

** The current that plays this part in weak interaction is not ordinary since the particle's charge is changed in β-decay. But this is immaterial as far as our argument is concerned

tion is analogous to the mutual induction coefficient for two solenoids.

A simple line of reasoning leads to a fundamental conclusion: the constant of weak interaction g is not dimensionless, it has the dimensions of length squared. Let us emphasize once again: this conclusion is due only to the fact that two and not one particle are emitted in the decay!

The appearance of a dimensional constant is a very serious thing. Let us recall our words about the similarity in nature. If the constant were dimensionless, the interaction would remain weak for any scale of phenomena. No similarity exists in the case of a dimensional constant, and this conclusion holds for the microcosm.

To evaluate this consequence we need also to know the value of g. From the neutron decay we can calculate that

$$\sqrt{g} \approx 10^{-16} \text{ cm} = 1 \text{ millifermi}$$

It can be expected that the interaction will remain weak in the range greater than this value. However, once we approach the boundary of distances of an order of 10^{-16} cm, the phenomena related to the formerly weak interaction will start playing a more and more important part. Weak interaction may become strong (unless forbidden by something about which nothing is known at present).

The gravitational field of the earth makes life impossible for too bulky an animal, and weak interaction somehow changes the conditions for the existence of excessively small particles. For very energetic particles, for which according to quantum mechanics the wavelength must become very small, we can expect the appearance of new phenomena in the range of weak interactions. However, to observe these new phenomena, accelerators must be available which should be more powerful than any of those existing or being in construction.

Neutrino

One of the main participants of the processes involving weak interaction is the neutrino and its partner, the antineutrino. But the neutrino is not the only particle which is responsible for all slow decays; many decays proceed without the neutrino. Hyperons usually decay by emitting only pions, and the disappearance of kaons is predominantly related to their transformation into pions.

Now we choose to dwell, among a number of various processes,

on neutrino decays, i. e. on decays involving electrons, muons, and neutrinos. We shall return below to the decays of kaons; and we shall ignore the decays of hyperons, merely listing them in the table on pp. 117-120.

The neutrino is in itself a very unusual phenomenon. Like photons, it has no rest mass, but it has an antiparticle. For a long time it was expected that the neutrino is a truly neutral particle and, similarly to photons, is emitted in an identical way both in the decay of a neutron and in that of an antineutron. But this expectation failed to be confirmed. The neutrino is like a tiny top which always flies in such a way that it screws into the space with the left-hand screw thread. Projectiles from artillery guns and bullets from rifles travel in the same way. It is clear that the direction of rotation of a bullet depends on the rifling of the barrel. But the neutrino always rotates leftward: nature has 'rifled' all its sources identically. If a bullet stops, its rotation ceases; if it ricochettes, its rotation may change to its opposite. But the neutrino cannot be stopped: either it vanishes altogether or travels at a constant speed equal to the speed of light. If we capture a neutrino from a far-away galaxy, we can be sure that it retains all the properties it possessed at the moment of birth (at any rate, this is the general point of view). Antineutrinos rotate as a screw with the right-hand thread, and in this they differ from neutrinos.

Although recently such a behaviour of particles appeared rather unusual, nowadays everybody got used to it, and the new generation of physicists hardly notices here any violation of habitual notions. Therefore we also should not be surprised. If the rotation, or helicity as it is termed, of neutrinos were their only essential property, one could be easily reconciled to it. But it turned out that not even two but four neutrinos exist, and this is something much more difficult to get used to.

The neutrino is emitted not only together with a positron, but together with a muon as well. For instance, a negative pion may decay by the following reaction:

$$\pi^- \to \mu^- + \bar{\nu}_\mu$$

and may also decay (although very rarely) as

$$\pi^- \to e^- + \bar{\nu}_e$$

Neutrinos involved in these two decays were found to be different. This was established by observing the reverse reaction.

Antineutrinos emitted from an atomic pile lead to the reaction

$$p + \bar{\nu}_e \rightarrow n + e^+$$

This reaction, which in a certain sense is the reverse of the neutron decay, has been actually observed. Antineutrinos were produced in the reactor in the β-decays of nuclei, therefore we have marked them by the subscript e (signifying that they accompany electrons).

When attempts were made to detect this reaction in collisions with antineutrinos, produced in accelerators together with muons, the search proved to be futile. The muon neutrino refused to convert into the electron. Another reaction was observed instead:

$$p + \bar{\nu}_\mu \rightarrow n + \mu^+$$

in which the muon neutrino was converted into a muon.

Neutrinos remember the circumstances of their birth. They never change either the direction of rotation or the ability to distinguish between an electron and a muon. It is impossible, using the primitive concepts on the structure of particles, even to imagine where the information on the type of the neutrino is recorded and what in the neutrino corresponds to the property which we denoted by the subscript e or μ. This subscript was easy to write on paper, but where is it 'imprinted' on a neutrino? How did nature manage to print a mark onto a particle which, according to our today's concepts, has no structure at all? Is it possible that what we would like to call its structure lies inside the region of 10^{-16} cm? In this case the physicist is in the position of a detective who is looking for something and does not even suspect what this something must be like.

The properties of a neutrino are related to one more problem concerning not the microcosm but stars. It is universally believed at present that the nuclear reactions deep inside stars constitute the source of star energy. Neutrinos must be one of the products formed in these reactions. According to theoretical estimates the number of these neutrinos must be sufficiently high to detect them on the earth provided sufficiently large setups were installed. The construction of large counters located in a cave was completed in 1968; calculation affirmed that these detectors were to detect the sun-emitted neutrinos. But in vain. Why did the neutrino flux prove to be lower than expected? Is it possible that the theory poorly accounted for complicated hydrodynamics of processes in the sun, or is our concept of the nuclear reactions taking place in the sun incorrect?

The experiments with the recording of neutrinos are being continued. These experiments are extremely difficult: mere 1 or 2 particles were expected to enter the detectors per diem. At present hypotheses are being worked out which could explain the failure of the experiment. So far we do not know the reason for this failure.

Unfortunately, neutrino and antineutrino fluxes from far-away stars are too small to expect their measuring be completed in the next several years. But when this possibility becomes feasible we shall be able to find out whether there are antiworlds in our universe or not. Neutrino fluxes constitute the only information channel which is capable of transmitting information on the anti-world. If the sun emits neutrinos, the anti-sun must emit anti-neutrinos!

And although we are to wait for quite a long time for such experiments, we cannot help being amazed that nature is arranged so that even the most fantastic hypothesis can in the long run be verified by experiments.

Muon

The solution to still another mystery, namely that of the existence of the muon, is also far from being unveiled.

The muon is very similar to the electron. It has the same charge, is produced in the same way in weak decays, and is equally unrelated to strong interaction. Briefly, nothing in the muon (with the exception of its heavy mass) reminds us of mesons. Its behaviour, similarly to that of the electron, is described by the same equation, only different masses must be substituted. And if we were surprised by the difference between two neutrinos, then here it seems inconceivable why there should be two particles e and μ which, despite the difference in mass (the muon is 206 times heavier than the electron), look almost like twins. Nobody understands what role is given by nature to this unique member of the elementary particle community.

A muon ends its life by decaying into an electron (a positron) and two neutrinos:

$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$$

$$\mu^- \to e^- + \bar{\nu}_e + \nu_\mu$$

The two neutrinos are different! This follows from the fact that they cannot annihilate. Because were they allowed to do that,

other types of decays could be observed. Such, for example, as

$$\mu^+ \to e^+ + \gamma$$

$$\mu^+ \to e^+ + e^- + e^+$$

But such decays have never been observed. Negative results in the search for muons' decays without neutrinos gave birth to a suspicion that the number of non-identical neutrinos is greater than that believed at the moment.

The history of the pion ends with the muon decay. A charged pion finally decays into four particles:

$$\pi^+ \to \mu^+ + \nu_\mu \to e^+ + \nu_e + \nu_\mu + \bar{\nu}_\mu$$

On the other hand, we know that there also exists a direct decay

$$\pi^+ \to e^+ + \nu_e$$

The question is what part is played in nature by the fact that at the stage involving the muon the decay is delayed (by two millionths of one second), which results in an extra pair of neutrinos. This confirms even further the suspicion that the necessary solution is far from simple. Couldn't it prove to be the most important problem in elementary particle physics?

Charge Symmetry (*C*-Symmetry)

What made weak interactions unconventional was that they violated the laws which in other phenomena acted unfailingly and appeared to be almost obvious properties. Some time ago the violating of the energy conservation law was expected to be found in β-decay. But instead physicists discovered the neutrino – the particle which carried away energy. The unusual features of weak interactions were found to be related to very subtle properties of the particles themselves, to their symmetries for example, and to the charge symmetry (*C*-symmetry) in particular.

Already in the first years of the history of quantum mechanics it was established that any equation for a charged particle, which satisfied the requirements of the theory of relativity, has the solutions describing particles with both signs of charge. An equation cannot be written only for electrons – it will simultaneously describe positrons as well. Later it was found that particles with both signs exist not only on paper but in reality too. The first to be discovered was the positron. Pions and μ-mesons were discovered in pairs. And when the antiproton and the antineutron were discovered after a long search, the existence of antiparticles became

the recognized law of nature. All particles exist in nature either in pairs or are truly neutral, and in any process no preference is given to one of the charge signs. The $\pi^+ \to \mu^+ + \nu_\mu$ decay is in every respect similar to the $\pi^- \to \mu^- + \bar{\nu}_\mu$ decay. If we lost the means of measuring the electric charge, we simply could not detect the difference between these two decays. This symmetry is called charge symmetry.

Spatial Symmetry (*P*-Symmetry)

If a particle has no structure and no dimensions, it is natural to picture it as a point or as a very small sphere. But we know already that the neutrino cannot be thought of as a sphere: it revolves as a screw with the left-hand thread.

In this last statement one has to pay attention to neutrinos being similar specifically to the left-hand screw. There are no right-handed neutrinos, just as there are no left-handed anti-neutrinos.

The direction of rotation of a neutrino serves as a sign by which it can be distinguished from an antineutrino. In the case of charged particles this part is played by the electric charge and in the case of the neutron by its baryon charge. Nature has worked out an absolutely new solution for the neutrino, which is devoid of all these attributes. It is interesting that this solution can be realized only for a massless particle. The electron, for instance, could not have the spin always directed along, or against, the direction of motion.

Let us suppose that an electron is similar to the right-hand screw, i. e. that it rotates clockwise if we look at it from behind (so that the electron flies away from the observer). As long as the electron moves ahead of the observer, from his point of view it rotates clockwise. But suppose we overtook it. Looking back, we notice that the electron is falling behind and now rotates counterclockwise. Nothing happened to it, but the direction of rotation has changed to its opposite.

The electron's property to rotate clock- or counterclockwise cannot be even properly formulated: for one observer it will appear as the right-hand screw while for the other as the left-hand one. Look at the clock in the street: it has two different faces on opposite sides. But couldn't we install a single transparent face? Just imagine such a clock and you will realize why the direction of the electron's rotation cannot be indicated.

Then why is it true for a neutrino? For the only reason:

neutrinos move at the speed of light, and simply cannot be overtaken. We, so to say, always see the neutrino from one and the same side. This last expression is also arbitrary. The neutrino does not emit light, it cannot be seen, we can only record its birth and decay. And what is it doing between these important events? Are we still allowed to ask why all neutrinos revolve counterclockwise?

The hands of the clock move clockwise simply because the clock was so manufactured: it is quite possible to make a clock whose hands move in the opposite direction. The earth rotates around its axis as a right-hand screw owing to causes that are related to the conditions under which the solar system was formed; planets in other planetary systems can rotate in the opposite direction. Even in the solar system there are examples of opposite rotation: Phoebe, the ninth moon of Saturn, moves from west to east. Some of Jupiter's moons also move in the reversed direction.

The neutrino is born in various processes, conditions of its generation are different, but it is born invariably left-handed. Hence, this property of the neutrino is not related to the birth processes. We do not know why this is so. As a rule, people operate with the right hand better than with its mate, and we are certain that this is conditioned by the process of evolution. The neutrino had no evolution; thus we have no answer to the question why it is left-handed. Here physicists encountered the spatial asymmetry of the world, and we do not know whether there can be a world more symmetrical than ours.

Combined Symmetry (*CP*-Symmetry)

Thus, the neutrino is left-handed, and the antineutrino is right-handed. This property nevertheless reflects a profound symmetry. This symmetry is not of geometric nature; we cannot transform a neutrino into an antineutrino by rotating it, but only by reflecting the world in a mirror. If this operation were possible, if we could convert a left shoe into its mate (this great invention would simplify at one stroke the shoe manufacturing process), the neutrino's direction of rotation would change to its opposite. The information presented above signifies the discovery of a new fundamental property of the microcosm. As we have said, the neutrino is left-handed and the antineutrino is right-handed. No right-handed neutrinos or left-handed antineutrinos exist in nature.

If all the four possibilities were realized in nature, the microcosm

would look very symmetrical: it would be both *C*- and *P*-symmetrical. If we imagined a world containing, for example, only antineutrinos, all of them left-handed, such a world would be totally devoid of symmetry. In reality, the world still proves to be symmetrical, if only halfway so. In order to change from an antineutrino to a neutrino, we must first change to antiparticles (to consider, for instance, the decay of an antineutron instead of that of a neutron) and simultaneously reflect the neutrino in a mirror (this, of course, will be done by nature itself). The neutron decay is related to that of the antineutron decay in the same sense as the left shoe is related to its mate by two operations – the charge reflection and the mirror reflection.

Thus, the mirror reflection of a neutrino is an antineutrino. This symmetry is called the *CP*-symmetry, or the combined symmetry. Almost all phenomena possess this symmetry. This means that if we observe a process involving elementary particles, then the *CP*-symmetrical process exists (and is in principle observable).

If, for example, a neutron decays in a magnetic field, the electrons are predominantly emitted opposite the direction of the field. This means that in the antineutron decay the positrons will mostly fly along the direction of the field. Whence follows the rule: if in a statement concerning the properties of particles we replace particles by antiparticles and vice versa and simultaneously change the direction of rotation and that of the magnetic field to their opposites, a new statement will be valid provided the original one is true.

We must also note that truly neutral particles coincide with their mirror images. In this sense the truly neutral particles are similar not to shoes but to stockings.

Time Symmetry (*T*-Symmetry)

The most difficult symmetry to comprehend is the time symmetry, or *T*-symmetry. Our world is characterized by a simple property well-known even in classical mechanics, viz. the reversibility of phenomena. In mechanics any motion can be reversed. The velocities of particles can be replaced by opposite ones so that the system will start moving backwards, safely arriving at the starting point. Of course, this statement contradicts the reality: entropy increases in each real phenomenon (owing to friction or because of something else) and the past cannot be revived. But our mind is already accustomed to abstraction, we readily imagine people on the opposite side of the globe, so we have no difficulties in modelling

a frictionless world. Therefore we easily imagine such a frictionless world in which the equations of mechanics are valid.

The reversibility of the laws of mechanics is easily demonstrated on a billiard table. We only have to take into account that a billiard ball does not glide; it rolls revolving around its axis. However, even this complication can be taken into account if we note that in its reversed motion the ball will rotate in the reversed direction. The reversibility in time can be formulated more accurately as follows. If the motion of a system is described as a sequence of states each of which is characterized by specific coordinates and velocities, then the system can go through the same states in the reversed direction if all the directions of motion (all the velocities) are replaced by the opposite ones. Exactly such a picture will be seen on the screen if the film is run backwards. *T*-symmetry can be illustrated by means of motion-picture techniques, just as *P*-symmetry is demonstrated by means of a mirror. We can easily demonstrate an even more complicated symmetry, namely the combination of *P*- and *T*-reflections (*PT*-symmetry), if we watch the reversed motion picture in a mirror (which reflects the screen) or if we simply turn the film backside up. Of course, it must be kept in mind that if such a film is produced for scientific purposes the actors in it must be material points and solids, and not people. A man walking backwards does not look quite as natural as one walking forward, but this concerns our organic world, which possesses neither *P*- nor *T*-symmetry.

Only the laws of mechanics are symmetrical. The symmetry with respect to the time reversal can be expressed in a different way. It can be said that no mechanical device (i. e. the device without friction) can (according to the laws of classical mechanics) determine the direction of time. Any clock indicates the direction of time only because the stored energy is being converted into heat: in the long run it is the expenditure of energy which shows how much time has elapsed. In the case of sandglass the falling-down sand is heated up, in the spring-driven watch the energy of the spring is spent on overcoming friction in pinions and bearings, in radioactive clocks atoms decay and the energy of nuclei transforms into the kinetic energy of emitted particles. If we neglect friction, then, after watching a pendulum, we cannot even pose the question about the direction in which time flows for this pendulum.

Therefore, symmetry in classical mechanics is related, in the end, to conservation of energy.

The law of energy conservation is also valid in quantum mechanics, therefore all processes must be equally reversible from the standpoint of the laws of quantum mechanics. If it were not so, we would be able, at least in principle, to construct a perpetuum mobile (of at least the second order!). Nevertheless quantum mechanics injects something new into the problem of reversibility.

Decays of *K*-Mesons

Let us recall once again how beautifully arranged the microcosm appeared after the discovery of π-mesons. It became possible to understand why nucleons are attracted to one another: for this purpose nature provided nuclear forces and their quanta, pions. One could even imagine pions being composed out of nucleons and antinucleons. In other words, a few more efforts and the microcosm would reveal all its secrets. However, the dreams never came true.

The maximum number of new problems was brought about by the discovery of kaons, or *K*-mesons. We remind the reader that there are two of them: K^+ and K^0 (one is positively charged and the other is neutral). They have antiparticles, K^- and K^0. This quadruple amazes physicists for more than a decade by a variety of its properties so dissimilar to the properties of other particles.

The most unexpected surprise presented by kaons was that they violate all symmetry laws. Kaons are not subject to any of the three symmetries we were discussing above, i. e. *C*, *P* or *T*.

We already know that spatial symmetry may be violated: the revolving neutrino is the most outstanding example of an asymmetrical object of the microcosm. But this asymmetry was discovered for the first time already 12 years ago in decays of kaons, without any participation of neutrinos.

And here are more recent events. Let us imagine a beam of neutral kaons emerging from the accelerator. The experimentor observing it detects that some of kaons decay into two pions. This happens very rapidly and close to the place where kaons are born. Physicists call such kaons *short-lived* and denote them by K_S. Therefore a distinctive feature of K_S is its fast decay into two pions with a lifetime of about 10^{-10} s. But not all of the kaons decay so fast. Approximately one half of them travel further and in the end decay not into two but into three pions. Such kaons are called *long-lived* and are denoted by K_L. Their distinctive

feature is the three-pion decay with a lifetime of about 10^{-8} s. At first glance everything is fairly simple, the beam consisting of two types of kaons:

$$K_S \to 2\pi \quad \text{and} \quad K_L \to 3\pi$$

This is strange in itself. The accelerator produced kaons of only one sort: neutral K^0-mesons (with no subscripts). But kaons possess unusual properties. A newly-born kaon K^0 can also be described as a mixture of equal fractions of absolutely neutral particles K_S and K_L. We can also say that K_S in its turn is a mixture of an equal number of K^0 and $\bar{K}^0$, i. e. kaons and antikaons (therefore K_S is absolutely neutral). The same is true for K_L. Thus K^0 consists of K_S and K_L, while K_S consists of K^0 and $\bar{K}^0$. It is really difficult to make out what consists of what; but we have already mentioned that in the microcosm this question is meaningless.

We have never come across such a situation with particles either in classical or in quantum physics. However, a similar phenomenon is well known for light. The circularly polarized light can be described as a mixture of two linearly polarized beams, and the linearly polarized light can be composed of two beams, one with clockwise and the other with counterclockwise polarization. The properties of kaons reveal their wave nature. These properties are thoroughly investigated experimentally and there exist a number of processes in which K^0 turns into $\bar{K}^0$ (the chain is $K^0 \to K_L + K_S$; $K_L \to K^0 + \bar{K}^0$). This process of a particle turning into an antiparticle is unique. In the case of kaons it is possible only because neutral kaons have neither of the charges (electric or baryon). Hypercharge (or strangeness) is not conserved rigorously, it can only prolong the lifetime or the time of the transition. The only factor which could ban the $K^0 \to \bar{K}^0$ transformation is the charge symmetry law, but it is exactly this law that does not hold for these processes.

Thus, K^0-mesons emerged from the accelerator; among them K_S decayed very fast (over a period of 10^{-10} s) into two pions each, while K_L continued their flight, occasionally decaying into three pions (lifetime $\approx 10^{-8}$ s).

But then trouble was sensed. Very rarely, but still in appreciable numbers K_L decayed into 2π as well, although this was absolutely forbidden by the symmetry laws (the ban is stipulated by T-symmetry, but we do not see any way to explain this statement not using involved mathematics).

A new phenomenon developed from here. It is known that

particles decay by the law of the radioactive decay, their number decreasing exponentially. If at some moment of time $t = 0$ there was n_0 particles, then after the time interval t their number becomes

$$n = n_0 \cdot e^{-t/T}$$

The constant T is the mean lifetime of the particle.

If $K\S$ and $K\L$ decayed as one would expect them to, i. e. the former into 2π and the latter into 3π, the number of disintegrations would decrease exponentially, as is indeed observed in decays of radioactive nuclei. However, it was found that the decay of neutral kaons into 2π proceeds not like it happens to radioactive nuclei or other particles. The number of disintegrations decreases, with a slight oscillation, i. e. becomes somewhat higher and then somewhat lower than the expected value. The curve of the decrease in the number of decaying particles is modulated by a certain frequency, similarly to modulation of radiowaves fed into a receiver.

Theory shows that the frequency of these oscillations is due to the fact that $K\S$ and $K\L$ have different masses. The measured frequency allowed the mass difference to be determined. It proved to be equal to approximately 10^{-5} eV ($K\L$ is more massive). This result is fantastic: physicists succeeded in measuring the mass difference which is 10^{13} times smaller than the mass of the particle itself. This ratio is very close to that of the mass of human population to the mass of the earth itself. This is equivalent to detecting the presence of an ant on a large Egyptian pyramid by measuring the pressure exerted on the foundation.

The fact that the mass difference between two kaons is small did not come as a surprise. But nobody suspected that such a difference between masses could ever be measured. It took the discovery of a new effect, i. e. the breakdown of T-symmetry, to determine how much $K\L$ is heavier than $K\S$.

Nature always prepares a path where the researcher can finally get the answer to questions provided they are admissible. All that modern theory predicts is finally verified by experiment. But to do this scientists often have to give up certain well-set notions, having ascertained that they are nothing but prejudice.

Breakdown of Charge Symmetry

Among various paths of the kaon decay there are the following two:

$$K\L \to \pi^- + e^+ + \nu_e$$

$$K\L \to \pi^+ + e^- + \bar{\nu}_e$$

The particle K_2^0 is neutral and there is nothing odd in its decaying both into π^+ and into π^-. On the contrary, it would seem puzzling if the neutral kaon converted only into pions of the same sign. This would violate the charge symmetry (more precisely, *CP*-symmetry, because of the neutrino participation).

But nonetheless something of the sort did happen. The number of observed transformations of kaons into π^- exceeded that of transformations into π^+ by 0.3%. The world of kaons reveals a weaker tendency towards positive pions than towards negative ones.

The same phenomenon is observed in decays in which mesons participate:

$$K_2^0 \to \pi^- + \mu^+ + \nu_\mu$$
$$K_2^0 \to \pi^+ + \mu^- + \bar{\nu}_\mu$$

Again the decays involving π^- are 0.3% more frequent than those with π^+.

Here again everything is baffling: why this asymmetry is observed at all and why it is so small. In addition, this asymmetry was not found anywhere else (it is restricted exclusively to the decays of K_2^0). What is the part played by this phenomenon? Nobody knows that.

Maybe this is somehow connected with a very small mass difference between two kaons. At present we have no chance to detect the violation of charge symmetry in any other situation. Here we have to do with nothing but puzzles.

The history of the crumbling of symmetry laws started with the spatial symmetry. It was the neutrino which was responsible for the breakdown in the symmetry (provided the neutrino takes part in the process). But the number of paradoxes in processes without neutrinos proved to be bigger. Neutral kaons are at present the most surprising particles of the microcosm.

Most likely, we have not yet penetrated into the microcosm deeply enough and still are in for new shocks. But is there a possibility of understanding what we should beware of? Nothing definite can be said at present.

Conclusion

What is left after all the shocks? Each new discovery makes the structure of the microcosm still more and more complicated. The deeper we go into the microcosm, the more of its properties we observe. Of all the symmetry properties the only one remaining

unviolated is the great symmetry of the microworld, *CPT*-theorem. According to this theorem, for example, the masses of a particle and its antiparticle are exactly identical. Their lifetimes must be just the same. Though it may seem strange, until now sufficiently accurate experimental data on checking the *CPT*-theorem are lacking. It is known that lifetimes of π^+ and π^- coincide to the accuracy of 0.5%: only one or two not very accurate experiments have been carried out. But nobody knows whether the theorem is universally correct or some day we shall witness its breakdown. By the way, this would be a most unpleasant event: the whole mathematical apparatus of modern physics is based on the *CPT*-theorem. However, we cannot expect nature to take our convenience into consideration; if nature's structure does not comply with our present notions, new mathematics will undoubtedly be found for its description.

It is said that nature is like an open book. This comparison is poetical but the book itself is not easy to read. It is not enough that this book is written in a language legible to the select few, we do not even know where is the beginning and thus read the book from its middle. While little is read, everything seems clear and the deciphered pieces are nicely related to one another. But reading it further we bump into quite new characters, and new events no more result from what we already know. We have to return to the page from which the reading began, sometimes leaf a few pages back, often discovering by the way that these pages are not in the proper order. Thus, reading the book in both directions, we move along the intricate network of events and gradually disentangle their interrelations.

No end is seen to the open book of nature, nor has it a beginning. For instance, at present we deal with distances of the order of 10^{-14} cm. It is expected that at distances 100 times as small as these we are to come against principally new difficulties. But what next? It was not without reason that, discussing similarity, we compared the weak interaction to the gravitational one. If weak interaction becomes strong at distances of the order of 10^{-16} cm, then incomparably weaker gravitational interaction has a chance to become strong at distances which are even difficult to imagine: something about 10^{-32} cm. If such a penetration were possible, it would mean that the same forces that stipulate the structure of the universe operate in the most profound depths of the microcosm. This would not contradict the contents of the foregoing material. In particular, the evolution of the universe is due to nuclear reactions while its curvature may be caused by neutrino

fluxes. Thus the beginning of the book gets entangled with its end, and nothing in it is exposed as superfluous.

But are the distances of 10^{-16} and 10^{-32} cm indeed separated by a desert? Not necessarily. The breakdown of charge symmetry in kaon decays suggests that there should exist one more interaction, which is weaker than the weak interaction but stronger than the gravitational one. The superweak interaction joins in the play somewhere in the middle of this desert.

Interrelations in the world of elementary particles are difficult to comprehend. But we are becoming more and more positive that this world contains no unnecessary parts, that in the end the value of the electron charge is somehow related to the constant of the law of gravitation, which determines the motions of worlds, and that the strange behaviour of kaons is tied by some yet hidden strings to the birth of galaxies. By the way, it is from astrophysics that big discoveries must be expected at present. Deep inside stars processes take place, where strong gravitational fields are intricately combined with elementary particle processes. Neutron stars, whose existence was predicted by theorists a long time ago, have demonstrated their presence in the form of pulsars. Pulsars are stars whose emission intensity (in the range of radio frequencies and in visible light) oscillates with a surprisingly constant and precise periodicity. In some pulsars the period of oscillations varies only to the ninth or tenth decimal place. In these stars the density of matter reaches that of the nuclear matter: we see a pulsar as a gigantic nucleus.

Possibly even greater densities exist in collapsing stars, i. e. in stars compressing under the action of their own gravitational field. Nobody can say with any certainty whether such stars actually exist, but first suspicions that they do begin to appear.

It is spectacular that all these really strange objects are subject to the same laws which describe the motion of planets in the solar system or the scattering of nucleons by nucleons. Not a tiniest evidence exists that the fundamental laws of physics are violated somewhere. But we still know very little.

More than 200 years elapsed since Newton lived. We know the laws of quantum mechanics for fourty out of those two hundred years. The science of elementary particles now lives only through its youth. And astrophysics stands before us in all the glamour of its young beauty. Nobody can predict what it can bring in the future. But this is exactly the feature in which the main attraction of the open book of nature is revealed: he who began to understand cannot stop reading.

APPENDIX

We give a short review of the properties of elementary stable particles, i. e. particles with a low probability of decay (lifetime of 10^{-18} s and more). We distinguish between *hadrons*, i. e. heavy particles strongly interacting among themselves, and *leptons*, i. e. light weakly interacting particles. The table gives only one particle out of the particle-antiparticle pair. The antiparticle is oppositely charged and has the same mass and spin. In the column marked 'Mass' we give experimental limits which indicate the possible error of measurements.

Table

Particle	Symbol	Mass (MeV)	Spin	Charge	Hyper-charge	Comment
CLASSICAL FIELDS (long-range forces)						
Photon	γ	0	1	0	0	
Graviton	—	0	2	0	0	Not observed experimentally
LEPTONS						
Electron	e	$0.5110041 \pm \pm 0.0000016$	$^1/_2$	+1	0	Decays into: $e + \nu_e$
Muon	μ	$105.6594 \pm \pm 0.0004$	$^1/_2$	+1	0	Lifetime 2.2×10^{-6} s
Neutrino (electron)	ν_e	0	$^1/_2$	0	0	Experimental upper limit for mass $m(\nu_e) < 60$ eV
Neutrino (muon)	ν_μ	0	$^1/_2$	0	0	Experimental upper limit for mass $m(\nu_\mu) < 1.2$ MeV
HADRONS						
Nucleons						
Proton	p	$938.2592 \pm \pm 0.0052$	$^1/_2$	1	1	
Neutron	n	$939.5527 \pm \pm 0.0052$	$^1/_2$	0	1	Decays into: $p + e^- + \bar{\nu}_e$ lifetime 935 ± 14 s

Table (*continued*)

Particle	Symbol	Mass (MeV)	Spin	Charge	Hyper-charge	Comment
			Hyperons			
	Λ	1115.59 ± ± 0.05	$^1/_2$	0	0	Decays in various ways into: $p + \pi^-$ $n + \pi^0$ $p + e^- + \bar{\nu}_e$ $p + \mu^- + \bar{\nu}_\mu$ lifetime 2.5×10^{-10} s
	Σ^+	1189.42 ± ± 0.11	$^1/_2$	1	0	Decays in various ways into: $p + \pi^0$ $\Lambda + e^+ + \nu_e$ $n + \pi^+$ $n + e^+ + \nu_e$ $p + \gamma$ $n + \mu^+ + \nu_\mu$ lifetime 0.8×10^{-10} s
	Σ^0	1192.48 ± ± 0.11	$^1/_2$	0	0	Decays into: $\Lambda + \gamma$ lifetime less than 10^{-14} s
	Σ^-	1197.34 ± ± 0.10	$^1/_2$	−1	0	Decays in various ways into: $n + \pi^-$ $n + e^- + \bar{\nu}_e$ $n + \mu^- + \bar{\nu}_\mu$ lifetime 1.49×10^{-10} s (Σ^- is not the antiparticle for Σ^+!)
	Ξ^0	1314.7 ± ± 0.7	$^1/_2$	0	−1	Decays in various ways into: $\Lambda + \pi^0$ $\Sigma^+ + e^- + \bar{\nu}_e$ $p + \pi^-$ $\Sigma^- + e^+ + \nu_\mu$ $p + e^- + \bar{\nu}_e$ $\Sigma^- + \mu^+ + \nu_e$ $p + \mu^- + \bar{\nu}_\mu$ lifetime 3×10^{-10} s

	Ξ^-	1321.30 ± ± 0.15	$^1/_2$	−1	−1	Decays in various ways into: $\Lambda + \pi^-$ $\quad \Sigma^0 + e^- + \bar{\nu}_e$ $n + \pi^-$ $\quad \Sigma^0 + \mu^- + \bar{\nu}_\mu$ $\Lambda + e^- + \bar{\nu}_e$ $\quad n + e^- + \bar{\nu}_e$ $\Lambda + \mu^- + \bar{\nu}_\mu$ lifetime 1.7×10^{-10} s
	Ω^-	1672.5 ± ± 0.5	$^1/_2$	−1	−2	Decays into: $\Xi^0 + \pi^-$ $\Xi^- + \pi^0$ $\Lambda + K^- + K^0$ total number of observed decays – 30 lifetime 1.3×10^{-10} s
			Mesons			
Pions	π^+	139.576 ± ± 0.011	0	1	0	Decays into: $\mu^+ + \nu_\mu$ $e^+ + \nu_e$ $\pi^0 + e^+ + \nu_e$ lifetime 2.60×10^{-8} s
	π^0	134.972 ± ± 0.012	0	0	0	Decays into 2 photons lifetime 0.8×10^{-16} s
Kaons	K^+	493.84 ± ± 0.10	0	1	1	Decays in numerous ways into: $\mu^+ + \nu_\mu$ $\quad \pi^+ + \pi^- + e^+ + \nu_e$ $\pi^+ + \pi^0$ $\quad \pi^+ + \pi^- + \mu^+ + \nu_\mu$ $\pi^+ + \pi^- + \pi^0$ $\quad \pi^+ + \pi^+ + e^- + \bar{\nu}_e$ $\pi^0 + \mu^+ + \nu_\mu$ $\quad \pi^+ + \pi^+ + \mu^- + \bar{\nu}_\mu$ $\pi^0 + e^+ + \nu_e$ $\quad e^+ + \nu_e$
	K^0	497.79 ± ± 0.15	0	0	0	A neutral kaon is a mixture of two states (particles): 50% K_S and 50% K_L lifetime: $K_S - 0.86 \times 10^{-10}$ s $K_L - 5.1 \times 10^{-8}$ s

Table (*continued*)

Particle	Symbol	Mass (MeV)	Spin	Charge	Hyper-charge	Comment
						K_L is heavier than K_S by 0.5×10^{-5} eV K_S decays either into $\pi^+ + \pi^-$ or into $\pi^0 + \pi^0$ K_L decays into: $\pi^0 + \pi^0 + \pi^0$ $\pi^- + \mu^+ + \nu_\mu$ $\pi^+ + \pi^- + \pi^0$ $\pi^- + e^+ + \nu_e$ $\pi^+ + \mu^- + \bar{\nu}_\mu$ $\pi^+ + \pi^-$ $\pi^+ + e^- + \bar{\nu}_e$ $\pi^0 + \pi^0$
	η	$548.8 \pm$ ± 0.6	0	0	0	Decays into: $\pi^0 + \pi^0 + \pi^0$ $\pi^+ + \pi^- + \pi^0$ $\pi^0 + e^+ + e^-$ lifetime about 10^{-19} s
	ρ^0	$770 \pm$ ± 10	1	0	0	Decays into: $\pi^+ + \pi^-$ lifetime $< 10^{-22}$ s
	ω	$782.7 \pm$ ± 0.6	1	0	0	Decays into: $\pi^+ + \pi^- + \pi^0$ $\pi^+ + \pi^-$ $\pi^0 + \gamma$ lifetime $< 10^{-22}$ s
	φ	$1019.7 \pm$ ± 0.3	1	0	0	Decays into: $K^+ + K^-$ $\pi^+ + \pi^- + \pi^0$ $\eta + \gamma$ lifetime $< 10^{-22}$ s

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The book makes the reader acquainted with the present "state of art" and perspectives of quantum mechanics. The author exposes in original form the milestones in the history of the development of quantum-mechanical concepts and the difficulties in understanding them.

The book is intended for college students, instructors and teachers of technical and high schools, specialists and all those interested in the present state of the physical theory.